

CHAPTER 5

CULVERTS



NOTE: For trunkline projects, direct questions and comments to the Hydraulic Unit Supervisor, Environmental Services Section.

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If you require assistance accessing this information or require it in an alternative format, contact the Michigan Department of Transportation's (MDOT) Americans with disabilities Act (ADA) coordinator at Michigan.gov/MDOT-ADA

5.1 Introduction/Purpose

This chapter provides procedures for the hydraulic design of highway culverts, which are based on FHWA HDS 5 (2012). Examples and results of culvert analysis using FHWA HY-8 culvert analysis software are provided. In addition, the design philosophy contained in the *AASHTO Drainage Manual* (2014) is summarized.

5.2 Definitions

Annual Exceedance Probability (AEP) - The probability that the magnitude of the random variable (e.g., annual maximum flood peak) will be equaled or exceeded each year, often expressed as a percentage.

Annual Recurrence Interval (ARI) - The average time interval between occurrences of a hydrologic event of a given or greater magnitude, usually expressed in years. The ARI is the reciprocal of the AEP of a hydrologic event.

Apron - Protective material placed on a streambed to resist scour.

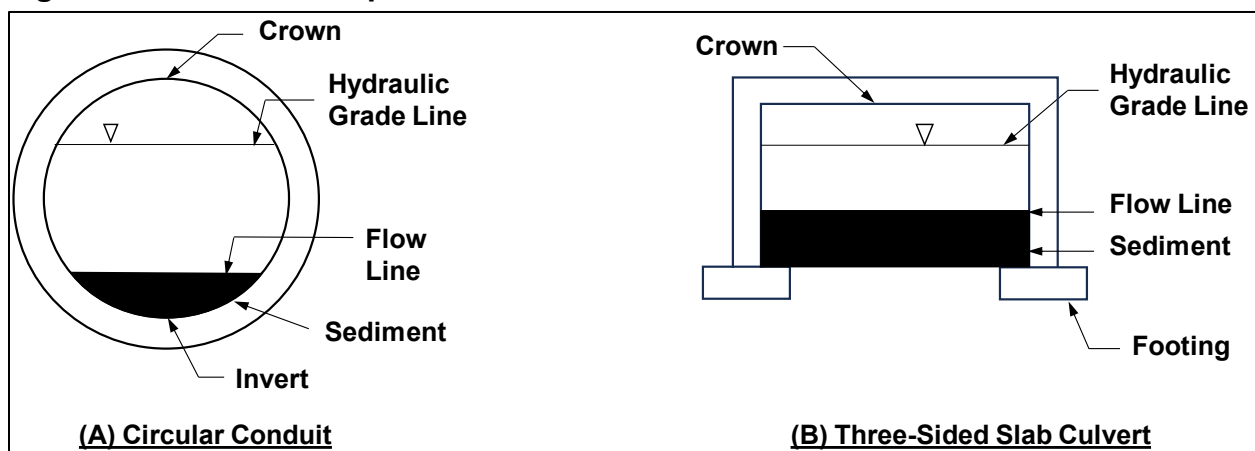
Clear Zone - A highway clear zone is an unobstructed, traversable area along a road or highway designed to allow a driver to safely recover from a vehicle that has left the roadway.

Cover - Distance from the outside top of the pipe or structure to the final grade of the ground surface or pavement.

Critical Depth (d_c) - In hydraulic analysis, the depth when flow has a Froude number of 1.0. The depth associated with the minimum total energy to pass a given flow through a given cross-section.

Crown - The highest interior elevation of a culvert, sewer, drain pipe, or stormwater tunnel. This may also be referred to as underclearance or low chord. Refer to **Figure 5.1**.

Figure 5-1. Culvert Components



Culvert - A structure that is usually designed hydraulically to convey flow through an embankment. The span length is less than 20 feet measured along the road centerline.

Cut-off Wall - A vertical wall, usually sheet piling or concrete, that extends below the channel bottom to scour-resistant material or the expected scour depth to reduce the risk of undermining. A cut-off wall is typically located at the end of the apron.

Energy Grade Line (EGL) - The plotted line that represents the total energy of flow at a location. It is the sum of the elevation head, the pressure head, and the velocity head.

Flow Line - The lowest physical surface elevation in a drainage system. For storm sewers, the flow line is the same as the invert. For recessed culverts, the flow line is the top of sediment inside the barrel. Refer to **Figure 5.1**.

Flow Type - The USGS has established seven culvert flow types which assist in determining the flow conditions at a culvert site. Diagrams of these flow types are provided in the design methods, **Section 5.4.1.8**.

Free Outlet - An outlet that has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.

Freeboard - The vertical distance between the design water surface elevation and a point of interest such as a low chord of a bridge beam, crown of a culvert, or specific location on the roadway grade, for example, the bottom of subbase grade.

Harmful Interference - Causing an increased stage or change in direction of flow of a river or stream that causes, or is likely to cause, any of the following: i) Damage to property, ii) A threat to life, iii) A threat of personal injury, iv) Pollution, impairment, or destruction of water or other natural resources. MCL 324.3103, R 323.1311g

Headcutting - Channel degradation associated with abrupt changes in bed elevation that generally migrates in an upstream direction. The occurrence can be natural or in response to channel cleanouts, dam removals, bridge/culvert installations, or increases in discharge.

Headwater (HW) - The water surface elevation on the upstream side of a culvert providing the energy to force water through the culvert.

Hydraulic Grade Line (HGL) - A plotted line coinciding with the level of flowing water in an open channel or conduit. In a closed conduit flowing under pressure, the HGL is the level to which water would rise in a vertical tube at any point along the pipe. It is equal to the EGL minus the velocity head ($V^2/2g$). Refer to **Figure 5.1**.

Hydraulic Jump - A rapid rise in the level of water when the water transforms from a supercritical to subcritical flow regime.

Improved Inlet - An inlet that has an entrance geometry which decreases the flow contraction hydraulic losses at the inlet, increasing the capacity of culverts flowing under inlet control conditions. Improved inlets are referred to as either side- or slope-tapered and sometimes are bevel edged.

Inlet Control - Occurs when the culvert barrel can convey more flow than the inlet will accept.

Invert - The lowest interior elevation of a culvert, sewer, or tunnel. Refer to **Figure 5.1**.

Mild Slope - For a given discharge, hydraulically mild slopes occur where critical depth is less than normal depth (subcritical flow).

Nomograph - A diagram that represents the relationship between multiple variable quantities by means of several scales, so arranged that an outcome can be found by drawing a straight line intersecting other scales at appropriate values.

Normal Depth (d_n) - The depth of flow in a pipe when the flow is uniform and steady and the water surface and pipe slope are the same. It occurs when the gravitational force of the water is equal to the friction drag along the pipe, and there is no acceleration of flow.

Ordinary High Water Mark - The line between upland and bottomland that persists through successive changes in water levels, below which the presence and action of the water is so common or recurrent that the character of the land is marked distinctly from the upland and is apparent in the soil itself, the configuration of the soil surface, and the vegetation. On an inland lake that has a level established by law, it means the high established level. Where water returns to its natural level as the result of the permanent removal or abandonment of a dam, it means the natural ordinary high water mark (MCL. § 324.30101). On Great Lakes, the ordinary high water mark is published in Section 32502 of Part 325 of NREPA.

Outlet Control - Occurs when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept.

Probability of Exceedance - The probability that the magnitude of the random variable (e.g., annual maximum flood peak) will be equaled or exceeded over a given time period, expressed as a percentage.

Slab Culvert - A culvert that is located on a footing and has a natural floor, also referred to as a three-sided box culvert.

Steep Slope - For a given discharge, hydraulically steep slopes occur where critical depth is greater than normal depth (supercritical flow).

Subcritical Flow - Depths of flow greater than critical depth.

Submerged Inlet - An inlet is submerged when the headwater is greater than 1.2 times the culvert diameter or rise.

Submerged Outlet - An outlet is submerged when the tailwater elevation is higher than the crown of the culvert.

Supercritical Flow - Depths of flow less than critical depth.

Tailwater - The depth of flow directly downstream of a storm sewer system or culvert, measured from the invert at the storm sewer system or culvert outlet.

Weir Flow - Flow calculation used when flow overtops the road embankment or other long hydraulic control with a well-defined head discharge relationship.

Symbols and acronyms used in this chapter are listed in **Appendix 5-A**.

5.3 Policy and Design Criteria

5.3.1 Introduction

The purpose of a culvert is to safely convey flow through an embankment or other type of flow obstruction. Select a culvert that best integrates engineering, economic, and environmental considerations. Consider the following factors when developing a culvert design:

- Topography
- Environmental impact
- Harmful interference
- Hydraulic equivalency
- Construction cost
- Future maintenance
- Traffic safety
- Nuisance considerations
- Coastal Impacts (refer to Chapter 9, Coastal Engineering)

Designing a culvert for a highway crossing of a floodplain involves using information from the other chapters in this manual that should be referenced when necessary.

5.3.1.1 Structure Types

This chapter is focused on culverts which are typically earth covered structures with both ends open, but may include a catch basin as an inlet and/or manholes to control bends and/or act as energy dissipator(s). Three-sided culverts, or slab culverts, require a more in-depth hydraulic analysis to complete scour calculations. Refer to Chapter 6, Bridge Hydraulic Design.

Culverts should not be confused with storm drains which are covered structures and are usually part of a system of pipes with multiple inlet points. Refer to Chapter 7, Inlet and Enclosed Storm Drainage Systems.

5.3.1.2 Hydrologic Methods

Culverts are analyzed under steady state flow conditions. Peak flow rates are developed using hydrologic methods that are discussed in Chapter 3, Hydrology. Steady state flow has the following characteristics:

- It is assumed for most culvert designs
- It is based on the peak discharge for the design storm hydrograph
- It yields a conservatively sized structure where temporary storage is available but not accounted for in the determination of design discharge

5.3.1.3 Hydraulic Computational Complexities

An exact theoretical analysis of culvert flow requires several complex computations:

- Analyzing non-uniform flow with regions of both gradually varying and rapidly varying velocities and flow depths.
- Determining how the flow type changes as the flow rate and tailwater elevations change.
- Applying backwater and draw-down calculations, energy, and momentum balance. Determine if hydraulic jumps occur and if they are inside or downstream of the culvert barrel.

This chapter outlines hydraulic analysis by using nomographs and computer programs. Consider the following when using nomographs:

- Requires a trial-and-error solution and provides reliable designs for many applications.
- Requires additional computations for tailwater, outlet velocity, hydrographs, routing, and roadway overtopping.
- Circular and box shapes nomographs are included in FHWA HDS 5 (2012). Nomographs for other shapes and improved inlets are included in FHWA HDS 5 (2001).

5.3.1.4 Computer Software Methods

FHWA HY-8, USACE HEC-RAS, and U.S. Bureau of Reclamation SRH-2D (via SMS) have the capability to analyze culverts. Features of each method are provided as follows.

HY-8 (Culvert Hydraulic Analysis Program):

- Uses the theoretical basis for the nomographs
- Computes tailwater, improved inlets, road overtopping, hydrographs, routing, and multiple independent barrels
- Develops and plots tailwater rating curves
- Develops and plots performance curves
- Free download

HEC-RAS (Hydraulic Engineering Center - River Analysis Systems):

- Allows users to perform steady flow calculations
- Requires additional survey compared to an HY-8 analysis
- Preferred software for denoting stream longitudinal profiles necessary for setting culvert inverts
- Typically required for trunkline crossings with drainage areas over 2 square miles
- HEC-RAS 2D available for 2D modeling
- Free download

SRH-2D (Sedimentation and River Hydraulics – Two-Dimension):

- Allows users to perform steady flow calculations
- Typically used for complex flow splits
- Requires license for use

The method used for culvert analysis is guided by the complexity of the system to be analyzed. In general terms, HY-8 can be used for relatively simple culvert analysis that focuses on the hydraulics of the culvert only. If the channel upstream and downstream of the culvert is part of the analysis, HEC-RAS is used. If a system is complex, consider a full 2D hydraulic analysis. Refer to Chapter 6, Bridge Hydraulic Design, Section 6.4.3.2 for additional guidance.

5.3.2 Culvert Policy

5.3.2.1 Federal Culvert Policy

For Federal policy, refer to Chapter 2, Policy and Procedures.

5.3.2.2 State Policy

For State policy, refer to Chapter 2, Policy and Procedures.

The plans must show magnitude, frequency, and water surface elevations for design and harmful interference flow rates for inland streams and / or culverts greater than 30 inches in diameter. Complete the Culvert Design Tables which are included in **Appendix 5-D**.

5.3.2.3 Culvert Hydrologic Design Criteria

The minimum culvert design flow criteria, including harmful interference and backwater analysis, is provided in **Table 5-1**. Pedestrian structures within the hydraulic influence of road facilities must match the requirements of the road facility.

Table 5-1. Minimum Culvert Design Criteria – AEP (ARI)

Roadway Classification	Design	Harmful Interference	Backwater
MDOT: Interstate, Freeways (Urban/Rural)	2% (50-year)	1% (100-year)	1% (100-year)
MDOT: Principal Arterial	2% (50-year)	1% (100-year)	1% (100-year)
MDOT: Minor Arterial	2% (50-year)	1% (100-year)	1% (100-year)
Local: Minor Arterial System with ADT<3000 VPD	4% (25-year)	1% (100-year)	1% (100-year)
Local: Collector System with ADT<3000 VPD	10% (10-year)	1% (100-year)	1% (100-year)
Local Road System	10% (10-year)	1% (100-year)	1% (100-year)
Pedestrian Crossings	10% (10-year)	1% (100-year)	1% (100-year)

Culvert operation should maintain or improve existing conditions and not increase backwater outside the right-of-way (ROW).

Hydraulic capacity and headwater depth are controlled by the conditions at either the inlet or the outlet of the culvert. Losses for a culvert flowing under outlet control would include expansion (at outlet), friction (culvert length and material type), and contraction (at entrance).

5.3.2.4 Hydraulic Analysis Requirements

Provide a culvert hydraulic analysis that determines the controlling headwater and outlet velocities for a range of flows per the minimum culvert design criteria in **Table 5-1**. Determine the existing and proposed culvert conditions for roadway overtopping up to the 1% AEP (100-year) flood event. Hydraulic analysis of culverts is performed using the procedures in FHWA HDS 5 (2012) or using computer programs such as HY-8, HEC-RAS, or SRH-2D. Include supporting data for the required review submissions.

For projects that include replacements, culvert liners, or extensions, perform an analysis of the existing and proposed structure using the same analysis method. Compare and evaluate the change between the existing and proposed conditions. Results are required to show no "harmful interference" to adjacent properties. Contact the MDOT Hydraulics Unit for assistance on trunkline projects.

Required documentation:

- For drainage areas less than 2 square miles (Planisware Task 3522), document hydrologic and hydraulic analysis for all culverts in the Drainage Study. Include the Culvert Design Tables (**Appendix 5-D**) in the report and plans for inland streams and / or culverts greater than 30 inches in diameter. Refer to the Drainage Study outline in Chapter 2, Policy and Procedures, Appendix 2-F, Drainage Study Task List.
- For drainage areas greater than or equal to 2 square miles (Planisware Task 3520), an environmental permit under Part 31 of NREPA from EGLE is required. The Hydraulics Unit (or a prequalified consultant with the analysis reviewed by the Hydraulics Unit) prepares a detailed hydraulic analysis. Prepare the Hydraulic Report per Chapter 6, Appendix 6-C requirements. MDOT will submit the report to EGLE for trunkline projects. Additional information can be found in Chapter 2, Policy and Procedures.

For additional information, refer to the MDOT Project Management Development/Design Task Manual.

5.3.2.5 Culvert Pipe Class Designation

Culvert pipes are designated by class, as indicated by the pipe's strength and load-carrying properties. The height of fill over the top of culvert pipe determines the class of pipe to use. Refer to the current MDOT Standard Specifications for Construction.

5.3.2.6 Culvert Usage Guidelines

All pipe culverts must be specified by class and diameter, e.g., Culv, CI A, 24-inch. The design life for culverts is 50 years, except driveway culverts and downspouts which is 25 years.

Perform a hydraulic analysis assuming worst hydraulic case for all available pipe materials in the class.

In some applications, a specific material for a culvert pipe is required exclusively, or a specific material is determined inappropriate for a particular location. Specify the pipe culvert class, material, and diameter (e.g., Culv, CI A, Conc, 42-inch) in the pay item. Identify the prohibited material by note on the plans. When a specific material is prohibited and its exclusion is not covered in the Standard Specifications, write a note to the file to describe the basis for exclusion. This information should also be forwarded to the construction engineer. An exception to when a project file note is needed is when an existing system is being extended with like material.

The following guidelines are specific to culverts:

- Perform a hydraulic analysis for all culverts
- Survey the following: topographic features, channel characteristics, high water information, existing structures, and other related site information as specified on the survey scope of services
- Avoid multiple culverts (parallel)
- Design culverts to accommodate debris and ice or make proper provisions for debris control
- Assemble design data and calculations in the project design files
- Provide for personnel and equipment access for maintenance, where practical

5.3.3 Culvert Environmental Permit Requirements

MDOT's Regional Environmental Permit Coordinators are required to review and coordinate all EGLE and USACE permit applications. EGLE coordinates, under Joint Permit Application, the USACE 404 Permit. The Water Pollution Control Act's 404 Permit is required for watercourses adjacent to wetlands, as listed in the USACE jurisdiction maps.

More details and information on applicable State laws can be found in Chapter 2, Policy and Procedures. The following State laws are applicable to culverts and are covered under the Joint Permit Application:

- Part 301, Inland Lakes and Streams, of the NREPA, Act 451 of Public Acts of 1994, as amended
- Part 31, Water Resources Protection, of the NREPA, Act 451 of Public Acts of 1994, as amended
- Part 303, Wetland Protection, of the NREPA, Act 451 of the Public Acts of 1994

- Part 325, Great Lakes Submerged Lands, of the NREPA, Act 451 of the Public Acts of 1994

5.3.4 Culvert Hydraulic Design Criteria

Design culverts to meet the following criteria:

5.3.4.1 Length and Slope

Choose the culvert length and slope to match approximate existing topography to the degree practical:

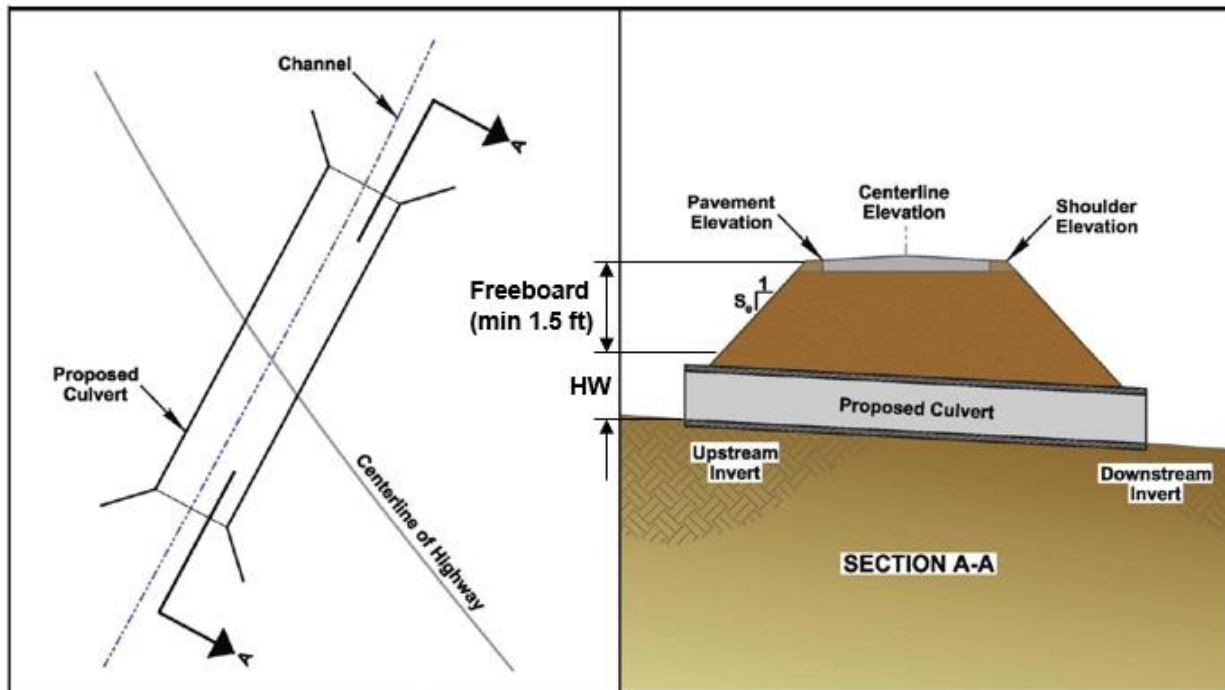
- Align the culvert with the stream centerline and the average channel slope extending 300 feet upstream and downstream of the culvert.
- For trunkline projects, coordinate with the Hydraulic Unit Supervisor and the Compliance and Mitigation Unit Supervisor for mitigation measures for existing culverts with inverts above the existing stream bottom.
- Minimize channel realignment work.
- Provide a culvert length to match the stable roadway embankment slope. Typical circular pipe sections are manufactured in 8-foot lengths.

5.3.4.2 Maximum Allowable Headwater

Allowable headwater is the depth of water ponded at the upstream end of the culvert during the design flood. The criteria that governs the maximum allowable headwater includes:

- Does not cause harmful interference to adjacent property.
- Allows for at least 1.5 feet of freeboard below the low edge of shoulder elevation during the design storm found in **Table 5-1**. Refer to **Figure 5-2** depicting freeboard at a culvert. Evaluate potential roadway overtopping locations near the culvert (within the contributing watershed).
- Is not greater than the elevation where flow diverts to a different watershed.

Figure 5-2. Roadway Cross-Section at Culvert - Freeboard (FHWA HDS 5, 2012)



5.3.4.3 Steep Slopes

Avoid the use of culverts on steep slopes unless maintaining the existing slope of a natural channel. When culverts on steep slopes flow full, reduced or negative pressures prevail along the boundaries of the culvert. Low pressures can cause joint failures and collapse the culvert pipe. Add air vents to reduce the risk of negative pressures along the steep section of the culvert. Air vents, such as additional manholes or PVC pipe vents, balance the air pressure inside the culvert.

5.3.4.4 Tailwater

Tailwater may or may not be impacted by downstream conditions. If no downstream water bodies or hydraulic controls are present, consider the following:

- Evaluate the hydraulic conditions of the downstream channel to determine a tailwater depth for a range of discharges, which includes the review discharge (refer to Chapter 4, Open Channels and Roadside Ditches, Section 4.4.1).
- Calculate tailwater using the standard step method at sensitive locations or use a single cross-section analysis. The standard step methodology is described in Chapter 4, Open Channels and Roadside Ditches, Section 4.4.3.7.
- If the culvert is operating with a free outfall, use the critical depth (d_c) plus pipe diameter (D) divided by two, expressed in formula as: $(d_c + D)/2$.
- Use the headwater elevation of a downstream culvert if it is greater than the channel depth.

If downstream water bodies or hydraulic controls are present, refer to Chapter 4, Open Channels and Roadside Ditches, Section 4.4.3.10.

5.3.4.5 Outlet Velocity

The outlet velocity at the culvert outlet during the design storm must be less than 6.0 fps or consistent with the velocity in the natural channel. Mitigate high outlet velocities with:

- A larger culvert to reduce the velocities to less than 6.0 fps.
- Energy dissipation only when the culvert has supercritical flow conditions. Refer to FHWA HEC-14 (2006) for design of dissipators. MDOT methods commonly used are drop structures comprised of a series of manholes, riprap basins (may require additional ROW), and stilling basins.

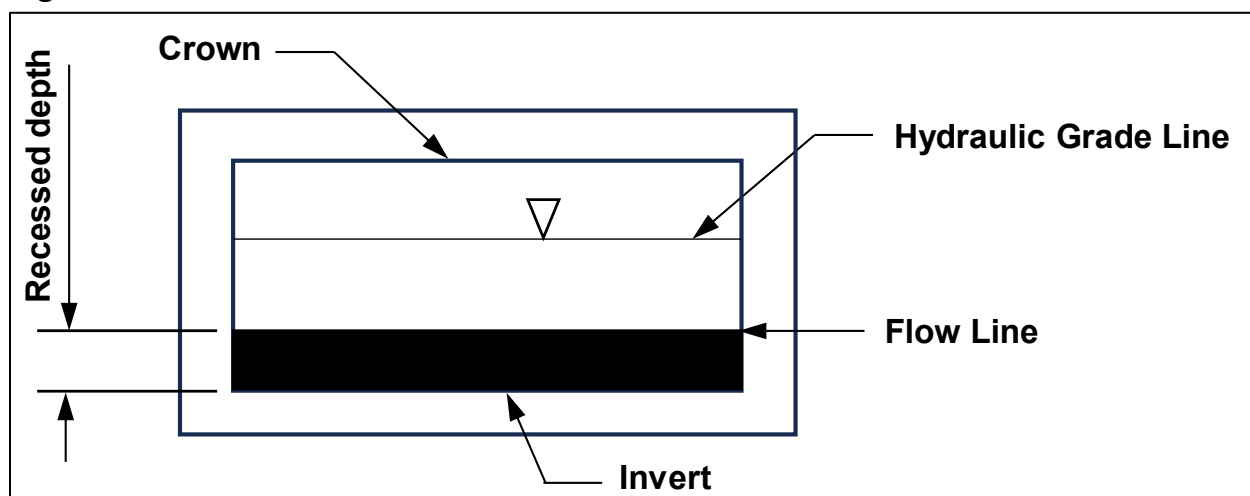
5.3.4.6 Erosion Protection

Place riprap or an equivalent soil erosion stabilization measure at both ends of a culvert. Develop riprap details and sizing based on guidance found in FHWA HEC-14 (2006). If conveying an inland stream use FHWA HEC-23 (2009) for design guidance.

5.3.4.7 Culvert Invert Placement

Recess the invert of a culvert below the stream or ditch flow line a minimum of 0.1 times the diameter or rise, or 6 inches, whichever is less, or a minimum of 1 foot for culverts on inland streams. The culvert elevation is referred to as the invert elevation on the plans to avoid confusion with the flow line of the waterway as shown in **Figure 5-3**. Refer to **Figure 5-3** for an example of a typical recessed depth for a box culvert. For recessed depths of 6 inches or less, the full culvert area is used for the hydraulic analysis. For recessed depths greater than 6 inches, exclude the recessed depth area in the hydraulic analysis.

Coordinate with the appropriate County Drain Commissioner for culverts on County Drains. Recess inverts a minimum of 1 foot below any future cleanout or legal drain elevation.

Figure 5-3. Box Culvert Invert Placement

Select the culvert size and shape based on engineering and economic criteria related to site conditions.

Consider the following culvert sizes as a minimum (unless supported by calculations and the backwater is within the MDOT ROW):

- Interstate system or divided highways - 24 inches
- Trunklines other than Interstate systems or divided highways - 18 inches
- Driveway culverts:
 - South of M-46 - 12 inches
 - M-46 and north in lower peninsula - 15 inches
 - Upper Peninsula - 18 inches
- Use arch or elliptical shapes only if required by hydraulic limitations, site characteristics, structural criteria, or environmental criteria.

5.3.5 End Treatments (Inlet or Outlet)

Select the culvert inlet type from **Table 5-2** or **Table 5-3**. After selecting type, determine the inlet coefficient, K_e , from Table 5-B-2 in **Appendix 5-B**. Consider safety when selecting end treatments which can be hazardous to errant vehicles. Headwalls or slope paving on the inlet end are required for culverts 48-inch diameter or larger.

Table 5-2 or **Table 5-3** summarize the guidelines for culvert end treatments inside the clear zone.

For culverts outside the clear zone, use engineering judgement to provide improved roadside safety when a small increase in cost is involved. Examples might include extending small culverts beyond the clear zone or placing a culvert slope end section outside the clear zone. Side slopes are 1V:3H and free of fixed objects or discontinuities that might interfere with an otherwise clear run out distance.

Refer to MDOT Road Design Manual Sections 7.01.11 and 7.01.30 for more information on clear zone criteria and guardrail at embankments.

Table 5-2. Transverse Culverts Inside Clear Zone

Culvert Size	End Treatment	Guidance
Circular: 18-inch and smaller	Existing end section	Leave in place, no grate required
Circular: 18-inch and smaller	Existing headwall	Remove headwall, extend if needed to meet slope. Fit with standard end section.
Circular: 18-inch and smaller	New culvert or current end section needs adjustment.	Design/extend to meet slope. Fit with standard end section.
Circular: 21-inch to 60-inch	Existing end section	Leave in place, but grate required. Alternative: Fit with culvert sloped end section.
Arch: 21-inch x 15-inch to 83-inch x 57-inch	Existing headwall	Remove headwall, extend if needed to meet slope. Fit with culvert sloped end section.
Elliptical: 14-inch x 23-inch to 48-inch x 76-inch	New culvert, or current end section needs adjustment.	Design/extend to meet slope, fit with culvert sloped end section
Slab and box culverts and pipes larger than listed	Headwalls	Extend beyond clear zone or shield with guardrail

Table 5-3. Longitudinal Culverts Inside Clear Zone

Roadway Classification	Culvert Size	Guidance
Freeway	Circular 12-inch	Standard end section Alternative: Use 15-inch pipe, culvert sloped end section
Freeway	Circular 15-inch and larger	Culvert sloped end section
Non-Freeway – Posted speed 40 mph or greater	Circular 12-inch and 15-inch	Standard end section. Alternative: Use 15-inch pipe, culvert sloped end section.
Non-Freeway – Posted speed 40 mph or greater	Circular 18-inch and larger	Culvert sloped end section
Non-Freeway – Posted speed 35 mph or less	All Sizes	Generally, no grates or sloped end sections required. Crash analysis and recommendations from Traffic and Safety Division may indicate a need to shield culvert ends in unique locations.
All roadways	Slab culverts, box culverts, and pipes larger than listed	Shield with guardrail per Road Design Manual

5.3.5.1 Culvert End Treatment Descriptions

Culvert end treatments are used to terminate culverts at embankments. Common types of end treatments are described as follows. Refer to **Appendix 5-C** for example photos and entrance loss coefficients.

Projecting Inlets or Outlets

- Extend beyond the roadway embankment
- Are susceptible to damage during roadway maintenance and from errant vehicles
- Have poor hydraulic efficiency for thin materials

Mitered Inlets

- Are hydraulically more efficient than thin edge projecting
- Are mitered to match the fill slope
- Include anchoring the inlet to strengthen the weak leading edge for culverts 48-inch diameter or larger

Outlet Headwalls (MDOT Road Standard Plan R-85-Series)

- Prohibit use where they will be exposed to traffic in the clear zone, regardless of which way they face, unless they are in an area protected by guardrail
- Require a baffle or other energy dissipation structure for the lower ends of steep culverts with outlet velocity greater than 6 fps. Refer to FHWA, HEC-14 (2006) for additional energy dissipation guidance.

Inlet Headwalls with Bevel Edges

- Increase the efficiency of a culvert
- Provide embankment stability and embankment erosion protection
- Protect against buoyancy (refer to **Section 5.4.1.3** for related designs on buoyancy protection)
- Shorten the required structure length

Culvert Safety Sloped End Sections (MDOT Road Standard Plan R-95-Series)

Install culvert safety sloped end sections on concrete or metal culverts within the clear zone. Culverts that can be equipped with the culvert sloped end sections include:

- Circular pipe culverts sizes 15-inch to 60-inch
- Arch pipes 21-inch x 15-inch through 83-inch x 57-inch
- Elliptical pipes 14-inch x 23-inch through 48-inch x 76-inch

Consider the following when culvert safety sloped end sections are used:

- Limit use on regulated streams due to risk of clogging with debris
- Culvert safety sloped end sections are considered mitered inlets for hydraulic calculation purposes
- Specify toe plates extension in the plans

Commercial End Sections (MDOT Road Standard Plan R-86 and R-88-Series)

Install precast concrete or steel end sections on corrugated metal, smooth-lined corrugated plastic, or concrete pipe outside the clear zone. Culverts between 12-inch and 84-inch can be equipped with commercial end sections.

Consider the following when commercial end sections are used:

- Minimizes embankment erosion and incurs less damage from maintenance
- May improve projecting metal pipe entrances by increasing hydraulic efficiency, reducing the accident hazard, and improving their appearance
- Equal to a headwall hydraulically, but can be equal to a beveled or side-tapered entrance if a flared, enclosed transition takes place before the barrel
- Show concrete footing for R-86 on plans
- Specify toe plates extension in the plans

5.3.5.2 Boxes/Slab End Treatments

5.3.5.2.1 Headwalls and Wingwalls

- Required for all crossings
- Provide the best hydraulic efficiency when the flare angle is between 30 and 60 degrees
- Grade a low flow channel, matching the existing cross-section, through the wingwalls up to the culvert faces to align stream to the center of the culverts on inland streams
- For three-sided structures, refer to Chapter 6, Bridge Hydraulic Design, for scour requirements.

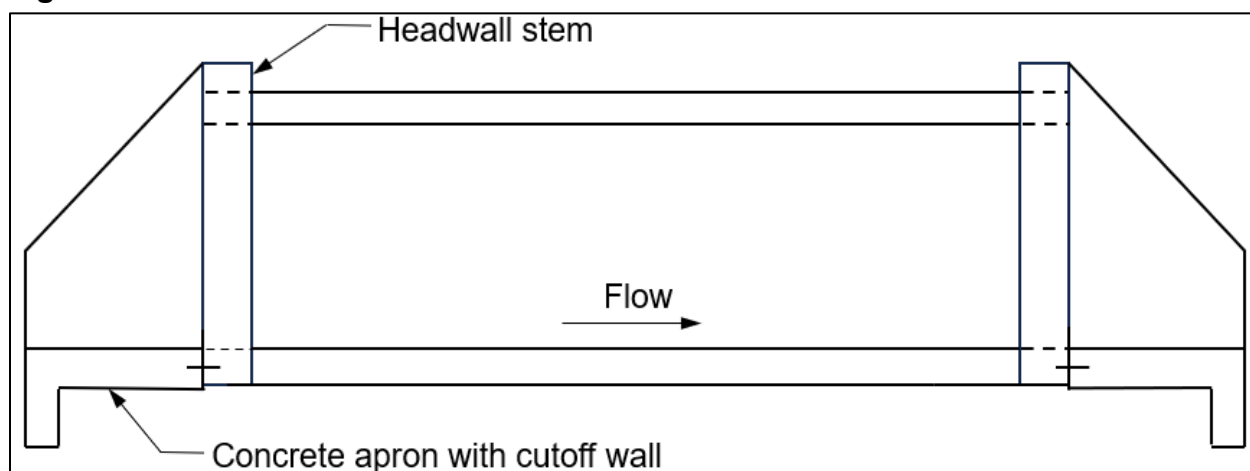
5.3.5.2.2 Concrete Aprons

- Required for all crossings with flared wingwalls
- Stabilize headwalls/wingwalls for total scour
- Extend at least one pipe diameter or rise upstream/downstream
- Do not protrude above the normal streambed elevation
- Refer to MDOT Bridge Design Manual for design guidance

5.3.5.2.3 Cut-off Walls

- Reduce the risk of piping along the culvert barrel and undermining at the culvert end treatments (headwalls and wingwalls)
- Use on all culverts with headwall
- Use a minimum depth of 2 feet
- Refer to **Figure 5-4** for an example of a box culvert with cut-off walls

Figure 5-4. Box Culvert with Cut-off Walls



5.3.5.3 Underdrain Systems

Provide underdrain systems for three-sided and box culverts. Use 4-inch or 6-inch underdrain pipe in accordance with subsection 909.07.B of the MDOT Standard Specifications for Construction.

5.3.6 Culvert Extensions and End Section Replacements

For EGLE permit applications and hydraulic analysis, the length of a culvert extension is defined as the length of the extension on both ends of the pipe, not including the length of the end sections. Note: The hydraulic analysis requirements are given in **Section 5.3.2.4**.

Use the same materials, shape, and opening when considering culvert extensions. Where culvert extensions on inland streams lead to elevated outlets (perched culvert), consider a culvert replacement to better match the existing channel.

5.3.6.1 Reinforced Circular Concrete Pipe Extensions

It is often necessary to extend circular culverts on rehabilitation projects. The concrete industry has changed its joint design over the years, and when old culverts are extended with new pipe, which is presently designed to be adaptable to gasketed joints, this may result in poorly fitted joints. To ensure tight joints and forewarn contractors of possible extra work required on applicable projects, the following General Plan Note should be placed on the note sheet:

General Note: Circular Culvert Extensions

The extension of existing circular concrete culverts on this project requires extra work to obtain a tight seal at the joint connecting new culvert pipe to existing culvert pipe. In addition to the requirements of MDOT Standard Specifications for Construction Section 401.03.C.4, completely fill the joint between the existing and new pipes with mortar to form a tight seal. Any extra work required to obtain tight joints will not be paid for separately but will be included in compensation for the unit price bid for the culvert pay item.

5.3.6.2 Extending Existing Box and Slab Culverts

For box culverts equal to or greater than 4-foot by 4-foot, use a precast concrete box extension with the appropriate connecting collar. Obtain the design of the extension from the Chief Structure Design Engineer for trunkline projects.

Extension of an existing slab culvert is not recommended.

5.3.7 Bedding and Filling Around Pipe Culverts

The bedding and filling around pipe culverts are constructed according to MDOT Road Standard Plan R-82-Series (fill applications) and R-83-Series (cut/trench applications)

which the MDOT Standard Specifications for Construction, Table 401-1: Pipe Alternatives for Culvert Classes, is based. For further discussion on bedding and filling, refer to MDOT Road Design Manual, Chapter 4, Section 4.05.12.

Refer to the MDOT Geotechnical Manual, Section 6.3.1 and 9.3.5 for culvert boring requirements. Reference the Geotechnical Service Section, Region Soils Engineer, or a Consultant Geotechnical Engineer recommendations for modifications to the standard backfill and bedding recommendations.

5.4 Design Guidance and Procedure

This section discusses the design approach and provides guidance for calculating culvert hydraulics.

5.4.1 Design Guidance/Approach

The following design factors are important to understand.

5.4.1.1 Control Section

A unique relationship between the flow rate and the upstream water surface elevation exists at the control section location. Inlet control is governed by the inlet geometry. Outlet control is governed by a combination of the culvert inlet geometry, the barrel characteristics, and the tailwater.

5.4.1.2 Minimum Performance

Minimum performance is assumed by analyzing both inlet and outlet control and using the highest headwater. The culvert may operate more efficiently at times (more flow for a given headwater level), but it will not operate at a lower level of performance than calculated.

5.4.1.3 Buoyancy Protection

Consider headwalls, endwalls, slope paving, or other means of anchoring to provide buoyancy protection for all flexible culverts (i.e., corrugated metal or plastic). Buoyancy is more serious with steepness of the culvert slope, depth of the potential headwater (debris blockage may increase), flatness of the upstream fill slope, height of the fill, large culvert skews, or mitered ends. If the allowable headwater depth to culvert height ratio (HW/D) is greater than 1.5, the inlet of the culvert will be submerged. Under this condition, provide an end treatment to mitigate buoyancy. Embankment stability may also be an issue once the culvert becomes submerged.

5.4.1.4 Relief Opening

Where multiple-use culverts or culverts serving as relief openings have their outlet set above the normal stream flow line, use special precautions, such as steel sheet piling or cutoff walls, to reduce the risk of headcuts or erosion from undermining the culvert outlet.

5.4.1.5 Sag Culverts

Sag culverts (sometimes called inverted siphons or sag lines) are used to convey water by gravity under roads, railroads, various types of drainage channels, and depressions. This closed conduit is designed to run full and under pressure. MDOT discourages the use of sag culverts because of safety and maintenance issues. For information on sag

culverts, refer to Chapter 7, Inlet and Enclosed Storm Drainage Systems and the Inverted Siphons section in *AASHTO Drainage Manual* (2014).

5.4.1.6 Slope or Side Tapered Inlets

Slope or side tapered inlets are flared culvert inlets with an enlarged face section and a hydraulically efficient throat section. MDOT discourages the use of tapered inlets. For information on tapered inlets, refer to the current version of the *AASHTO Drainage Manual*.

5.4.1.7 Sedimentation in Culverts

Sedimentation in culverts, particularly improved inlet or high velocity culverts, raises concern for related problems. Excessive sedimentation may block a portion of the culvert inlet, barrel, or outlet. It is sometimes necessary to assess potential sediment problems at a culvert. For procedures and guidance on this, refer to the current version of the *AASHTO Drainage Manual*.

5.4.1.8 Culvert Flow Types

Flow type numbers are used to help define how culvert flow is computed. The flow type numbers are based on USGS flow type numbers shown in **Table 5-4**. Refer to FHWA HDS 5 (2012) for more information.

Table 5-4. USGS Flow Types (FHWA HDS 5, 2012)

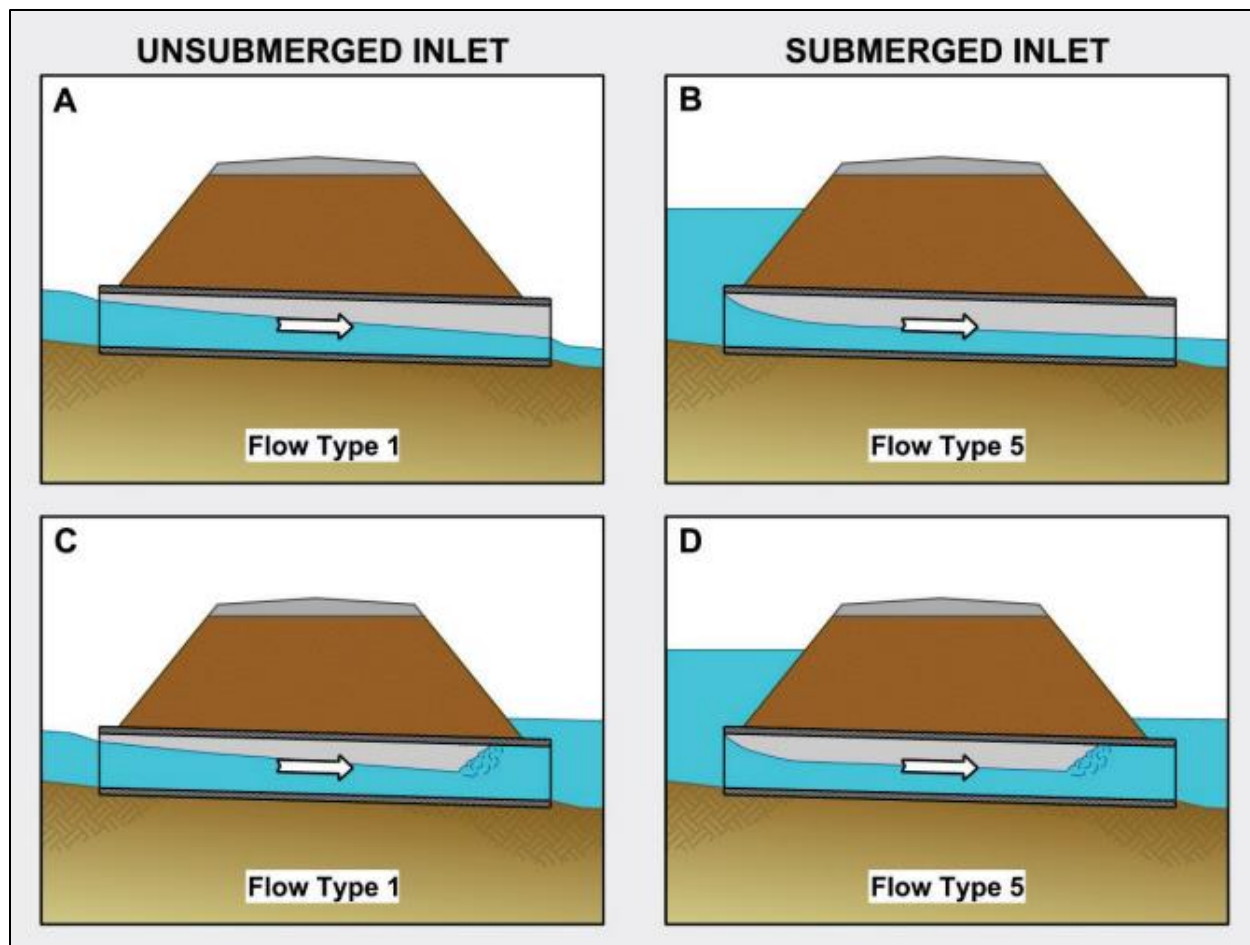
Flow Type	Flow Control	Submerged Inlet HW>D	Submerged Outlet TW>D	Length Full
1	Inlet	No	No	None
5	Inlet	Yes	No	None
2	Outlet	No	No	None
3	Outlet	No	No	None
4	Outlet	Yes	Yes	All
6	Outlet	Yes	No	Most
7	Outlet	Yes	No	Part

5.4.2 Inlet Control

For inlet control, the control section is at the upstream end of the barrel (the inlet). The flow passes through critical depth near the inlet and becomes shallow, high velocity (supercritical) flow in the culvert barrel. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet. Hydraulic characteristics downstream of the inlet

control section do not affect the culvert capacity. The upstream water surface elevation and the inlet geometry represent the major flow controls. The inlet geometry includes the barrel shape, cross-sectional area, and the inlet edge. Types of inlet control are illustrated in **Figure 5-5**.

Figure 5-5. Types of Inlet Control (FHWA HDS 5, 2012)



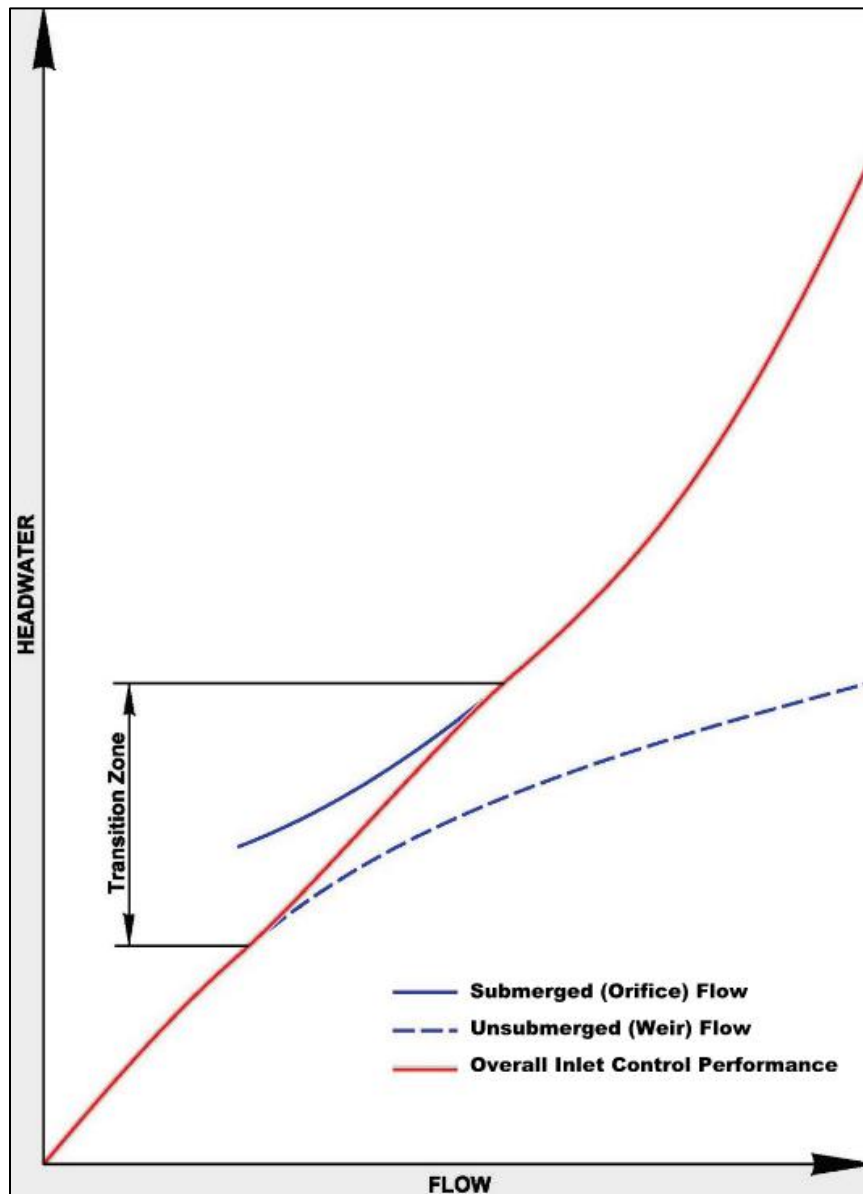
5.4.2.1 Headwater Factors

- Headwater depth is measured from inlet invert of the inlet control section to the surface of the upstream pool.
- Inlet area is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area.
- Inlet edge configuration describes the entrance type. Some typical inlet edge configurations are thin edge projecting, mitered, square edges in a headwall, and beveled edge. Refer to **Appendix 5-C** for photographs of inlet configurations.
- Typical inlet shapes are rectangular, circular, elliptical, and arch. Check for an additional control section if different than the barrel.

5.4.2.2 Hydraulics

There are three regions of inlet control flow. They are shown in **Figure 5-6**.

Figure 5-6. Inlet Control Curves (FHWA HDS 5, 2012)



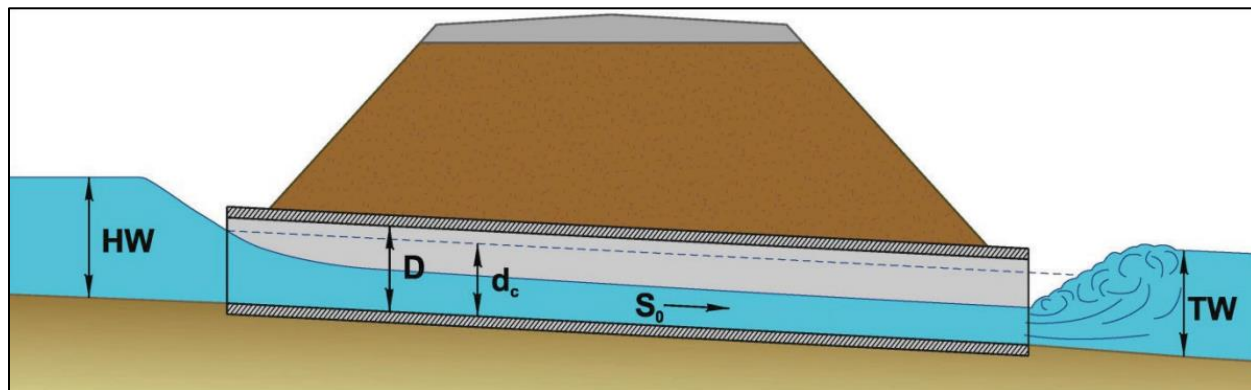
5.4.2.3 Unsubmerged Flow

For headwater below the inlet crown, the entrance operates as a weir as shown in **Figure 5-7**.

- A weir is a flow control section where the upstream water surface elevation can be predicted for a given flow rate

- The relationship between flow and water surface elevation must be determined by model tests of the weir geometry or by measuring prototype discharges
- Appendix A of FHWA HDS 5 (2012) contains the equations developed from model test data

Figure 5-7. Unsubmerged Flow (FHWA HDS 5, 2012)



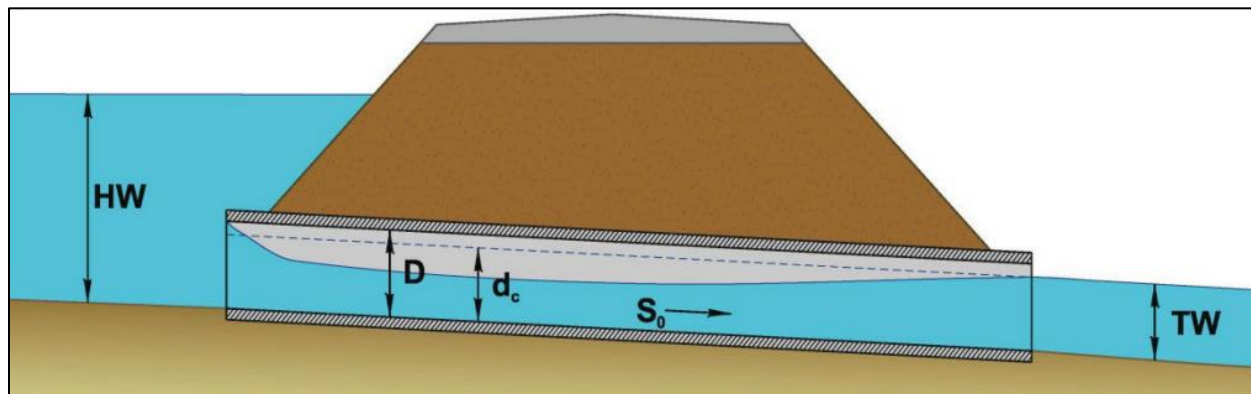
5.4.2.4 Submerged Flow

For headwaters above the inlet, the culvert operates as an orifice as shown in **Figure 5-8**.

An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section.

- The relationship between flow and headwater can be defined based on results from model tests
- Where practical, limit culvert operation with a submerged inlet for the design storm
- Appendix A of FHWA HDS 5 (2012) contains flow equations developed from model test data

Figure 5-8. Submerged Flow (FHWA HDS 5, 2012)



5.4.2.5 Transition Zone

The transition zone is located between the unsubmerged and the submerged flow conditions where the flow is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves.

For culverts on hydraulically steep slopes (slope greater than the slope that would produce critical depth), the U.S. Bureau of Reclamation describes a situation where the control alternates between inlet control and some downstream point (1987). If the headwater depth to culvert height ratio (HW/D) is greater than 1.2, the control is normally at the inlet. As the discharge increases, channel friction or local disturbances may force the level to flow full near the outlet, sealing the downstream end. This condition vacates trapped air causing the flow to be at sub-atmospheric pressure. This condition increases the discharge. The increased discharge causes a deeper draw-down that may bring more air into the pipe. This air lowers the discharge and increases the negative pressure on the pipe. This cycle will repeat with fluctuating pressures that cause a pulsating action on the pipe and vibrate the embankment. The pulsation may become so strong that damage to the pipe section and/or joints could lead to structural failure of the pipe.

When the headwater condition is such that HW/D is greater than 1.5, the entrance draw-down may be insufficient to interface with the fill-flow action and a steady state of full pipe flow will likely occur, thereby, eliminating the pulsation.

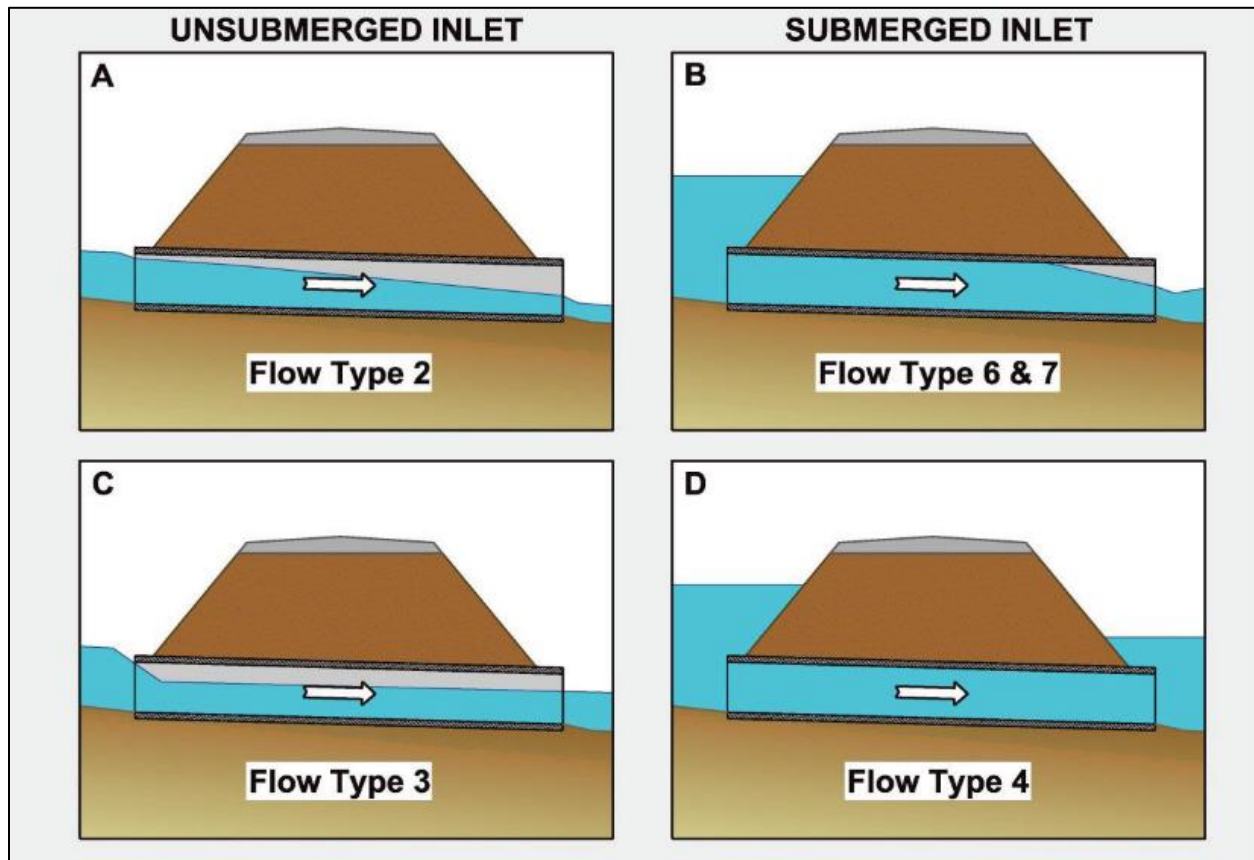
5.4.2.6 Nomographs

The inlet control flow vs. headwater curves are the basis for constructing the inlet control design nomographs. Note that in the inlet control nomographs, headwater is measured to the total upstream energy grade line including the approach velocity head. Nomographs can be found in FHWA HDS 5 (2012).

5.4.3 Outlet Control

For outlet control, the control section for a culvert is located at the barrel exit or further downstream. Subcritical or pressure flow exists in the culvert barrel under outlet control conditions. The geometric and hydraulic characteristics of a culvert play a role in determining its capacity: tailwater elevation at the outlet, slope, length, and barrel roughness. The tailwater depth is either assumed to be critical depth near the culvert outlet or the downstream channel depth, whichever is higher. The inlet control factors also influence culverts in outlet control. Types of outlet control are illustrated in **Figure 5-9**.

Figure 5-9. Types of Outlet Control (FHWA HDS 5, 2012)



The following factors, as defined, influence outlet control:

- **Barrel Roughness** – A function of the material used to fabricate the barrel. Typical materials include concrete, plastic, and corrugated metal. The roughness is represented by a hydraulic resistance coefficient such as the Manning's n value. Typical Manning's n values are presented in **Appendix 5-B**.
- **Barrel Area** – Area measured perpendicular to the flow.
- **Barrel Length** – Total culvert length from the entrance crown to the exit crown of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually necessary to begin the design process.
- **Barrel Slope** – Actual slope of the culvert barrel.
- **Tailwater Elevation** – Tailwater is based on the downstream water surface elevation. Backwater calculations start from a downstream control, a normal depth approximation in the channel, or critical depth just inside the culvert. The largest of the three conditions is considered the tailwater.

5.4.3.1 Hydraulics

Full flow in the culvert barrel is assumed for the analysis of outlet control hydraulics, unless partially submerged. Use partial hydraulic elements or a computer program

utilizing a standard step method for partially submerged conditions. Outlet control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool. **Figure 5-10** shows the outlet control energy and hydraulic grade lines for a range of inlet and outlet conditions and **Figure 5-11** shows the energy and hydraulic grade lines during full flow. An example problem is provided in **Section 5.4.8**.

Figure 5-10. Outlet Control Energy and Hydraulic Grade Lines (FHWA HDS 5, 2012)

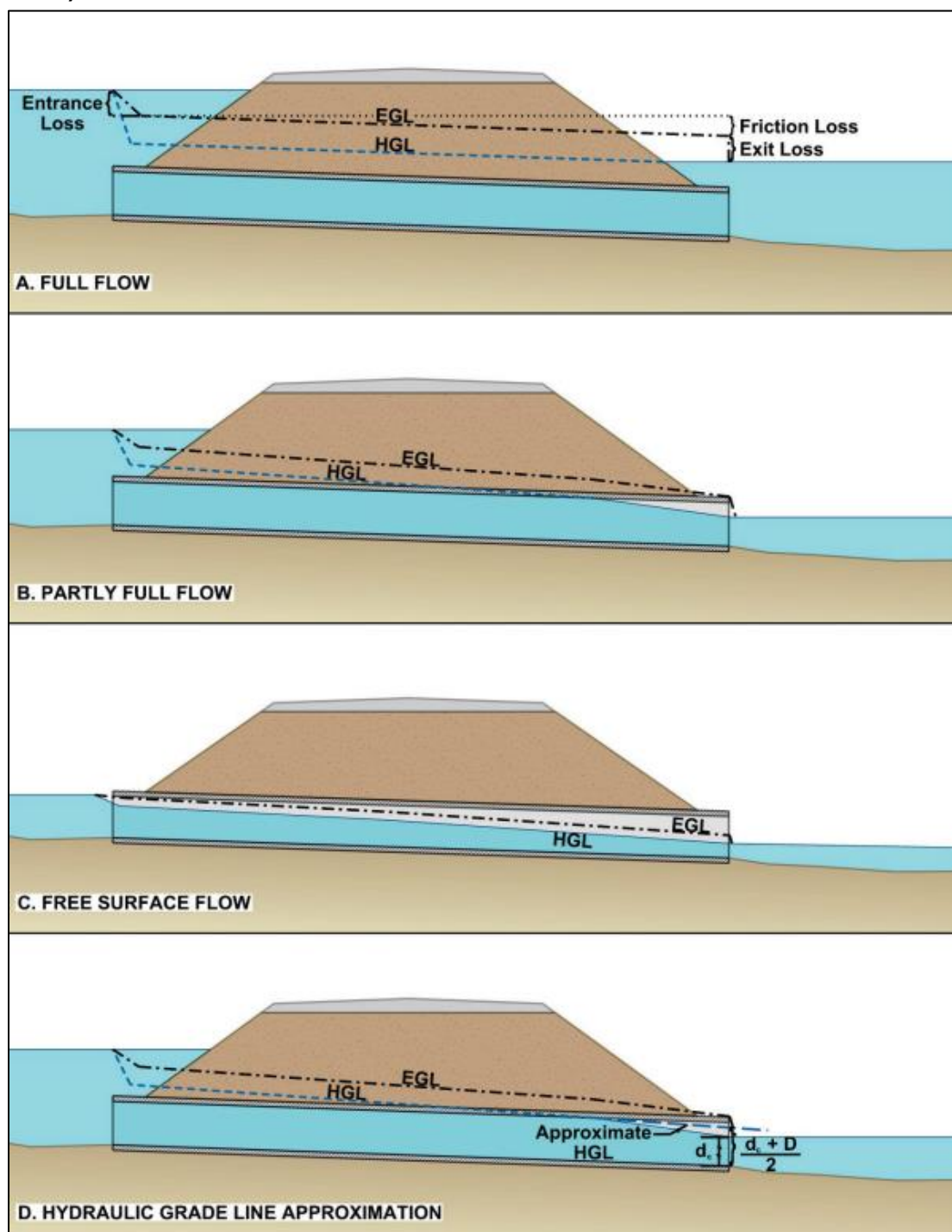
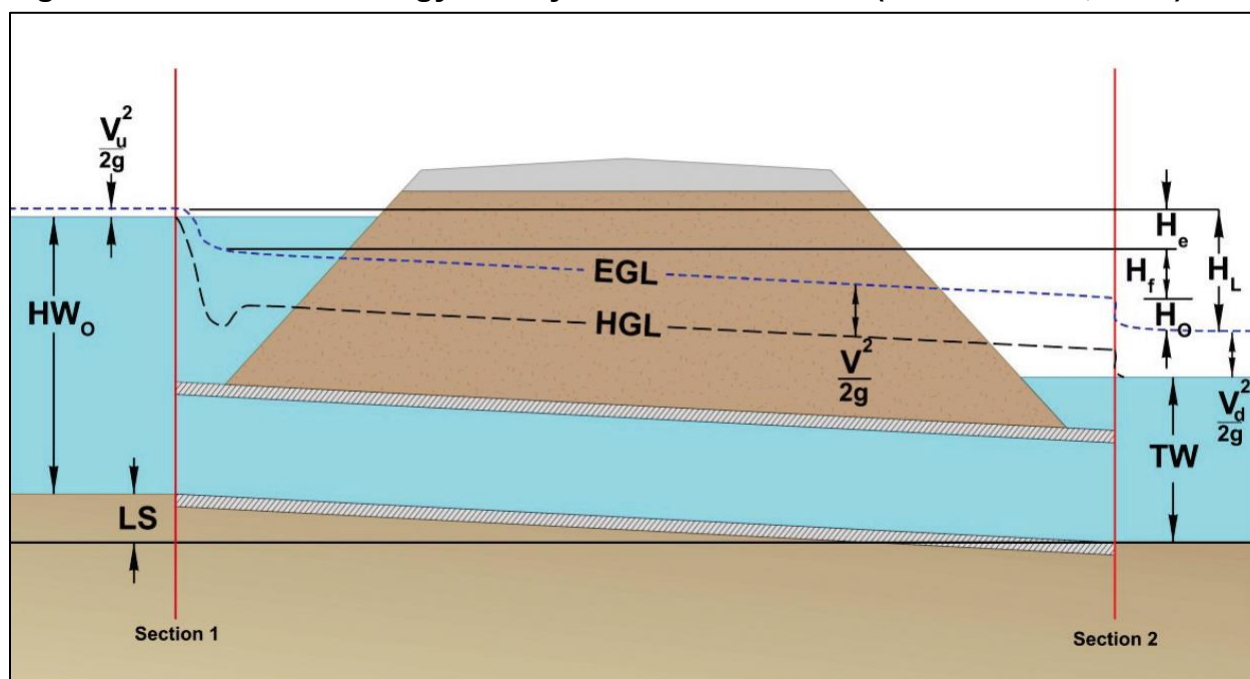


Figure 5-11. Full Flow Energy and Hydraulic Grade Lines (FHWA HDS 5, 2012)



Losses

$$H_L = H_e + H_f + H_o + H_b + H_j + H_g \quad (5.1)$$

Where:

- H_L = total energy loss, ft
- H_e = entrance loss, ft
- H_f = friction losses, ft
- H_o = exit loss (velocity head), ft
- H_b = bend losses, ft (refer to FHWA HDS 5, 2012)
- H_j = losses at junctions, ft (refer to FHWA HDS 5, 2012)
- H_g = losses at grates, ft (refer to FHWA HDS 5, 2012)

Barrel velocity

$$V = \frac{Q}{A} \quad (5.2)$$

Where:

- V = average barrel velocity, fps
- Q = flow rate, cfs
- A = full cross-sectional area of flow, sft

Velocity head

$$H_v = \frac{V^2}{2g} \quad (5.3)$$

Where:

H_v = velocity head, ft

g = acceleration due to gravity, 32.2 ft/s²

Entrance loss

$$H_e = K_e \left(\frac{V^2}{2g} \right) \quad (5.4a)$$

Where:

K_e = entrance loss coefficient (refer to Table 5-B-2 in **Appendix 5-B**)

Friction loss

$$H_f = \left(\frac{K_u n^2 L}{R^{1.33}} \right) \left(\frac{V^2}{2g} \right) \quad (5.4b)$$

Where:

K_u = 29 in English Units

n = Manning's roughness coefficient (refer to **Appendix 5-B**)

L = length of the culvert barrel, ft

R = hydraulic radius of the full culvert barrel = A/P , ft

A = cross-sectional area of the barrel, sft

P = wetted perimeter of the barrel, ft

Exit loss

$$H_o = 1.0 \left[\left(\frac{V^2}{2g} \right) - \left(\frac{V_d^2}{2g} \right) \right] \quad (5.4c)$$

Where:

V_d = channel velocity downstream of the culvert, fps
(Usually neglected, refer to **Equation 5.4d**)

$$H_o = H_v = \frac{V^2}{2g} \quad (5.4d)$$

Bend loss, junction loss, and grate loss are usually neglected because they are not common in culverts, but their loss takes the form of $H = K(V^2/2g)$. Each has its own table of K values listed in FHWA HDS 5 (2012), Chapter 5.

Neglecting the change in velocity from inlet to outlet, and the losses from bends, junctions, or grates, **Equation 5.1** reduces to **Equation 5.5**.

$$H_L = \left[K_e + 1 + \left(\frac{29 n^2 L}{R^{1.33}} \right) \right] \left[\frac{V^2}{2g} \right] \quad (5.5)$$

5.4.3.2 Energy Grade Line

The energy grade line represents the total energy at any point along the culvert barrel. Equating the total energy at Sections 1 and 2, upstream and downstream of the culvert barrel in **Figure 5-11**, the following relationship results:

$$HW_o + LS + \left(\frac{V_u^2}{2g} \right) = TW + \left(\frac{V_d^2}{2g} \right) + H_L \quad (5.6)$$

Where:

- HW_o = headwater depth above the entrance invert in outlet control, ft
- LS = drop through culvert, ft
- V_u = approach velocity, fps
- TW = tailwater depth above the outlet invert, ft
- V_d = downstream velocity, fps
- H_L = sum of all losses (**Equation 5.1** or **5.5**)

Note: If working in a known vertical datum, the LS term is not used.

5.4.3.3 Hydraulic Grade Line

The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel lines separated by the velocity head, except at the inlet and outlet where velocity is ignored.

Solving the culvert equation for the full flow, partly full flow, and open channel flow is described in the following sections.

5.4.3.4 Full Flow

The culvert barrel is flowing full as shown in **Figure 5-12** and the following assumptions are true:

- V_u is small. The velocity head is a part of the available headwater (HW) used to convey the flow through the culvert.

- V_d is small. The velocity head can be neglected.
- **Equation 5.6** becomes:

$$HW_o = TW + H_L - LS \quad (5.7)$$

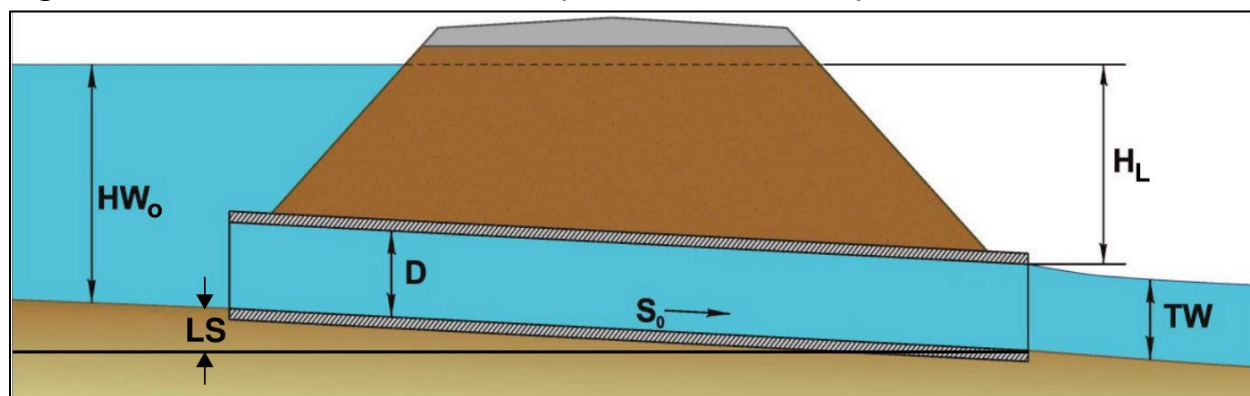
Where:

HW_o = headwater height above inlet invert for a culvert in outlet control, ft

H_L = total energy loss, ft (**Equation 5.5**)

Note: If working in a known vertical datum, the LS term is not used.

Figure 5-12. Full Flow in the Culvert (FHWA HDS 5, 2012)

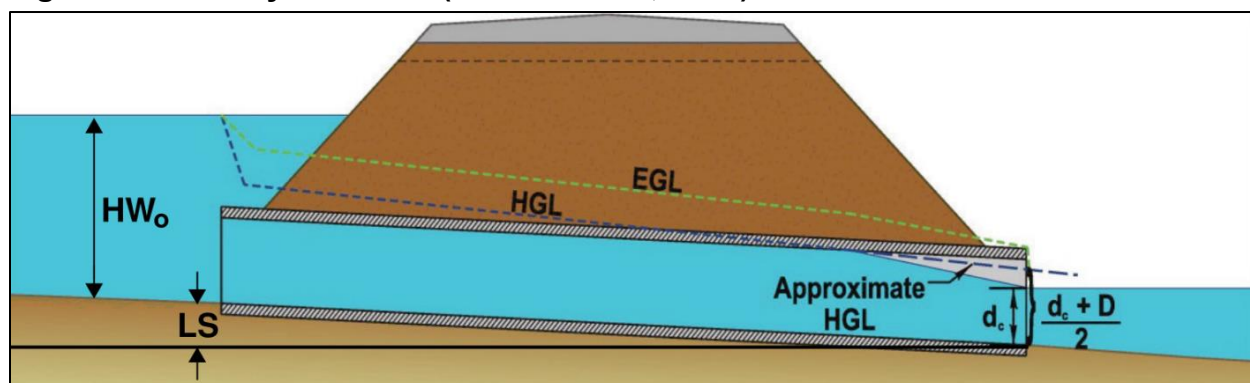


5.4.3.5 Partly Full Flow

Equations 5.1 through **5.7** were developed for full barrel flow. The equations also apply to the flow situations which are effectively full flow conditions, if $TW < d_c$, (refer to **Figure 5-13**).

- Backwater calculations may be required which begin at the downstream water surface and proceed upstream. If the depth intersects the top of the barrel, a full flow extends from that point upstream to the culvert entrance.

Figure 5-13. Partly Full Flow (FHWA HDS 5, 2012)



5.4.3.6 Open Channel Flow

The approximate method for open channel flow is based on numerous backwater calculations performed by the FHWA staff, it was found that the hydraulic grade line pierces the plane of the culvert outlet at a point approximately halfway between critical depth and the top of the barrel or $(d_c + D)/2$ above the outlet invert. Use TW if it is higher than $(d_c + D)/2$. The following equation should be used:

$$HW_o = h_o + H_L - LS_o \quad (5.8)$$

Where:

h_o = the larger of TW or $(d_c + D)/2$, ft

Note: If working in a known vertical datum, the LS_o term is not used.

Adequate results are obtained down to a $HW = 0.75D$. For lower headwater, backwater calculations are required.

(Refer to **Figure 5-14** if $TW < d_c$ and **Figure 5-15** if $TW > d_c$)

Figure 5-14. Open Channel Flow when $TW < d_c$ (FHWA HDS 5, 2012)

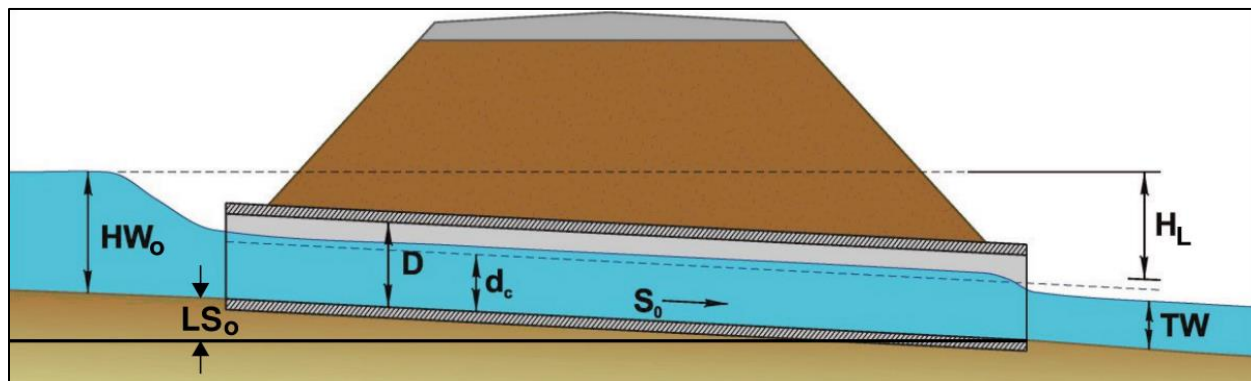
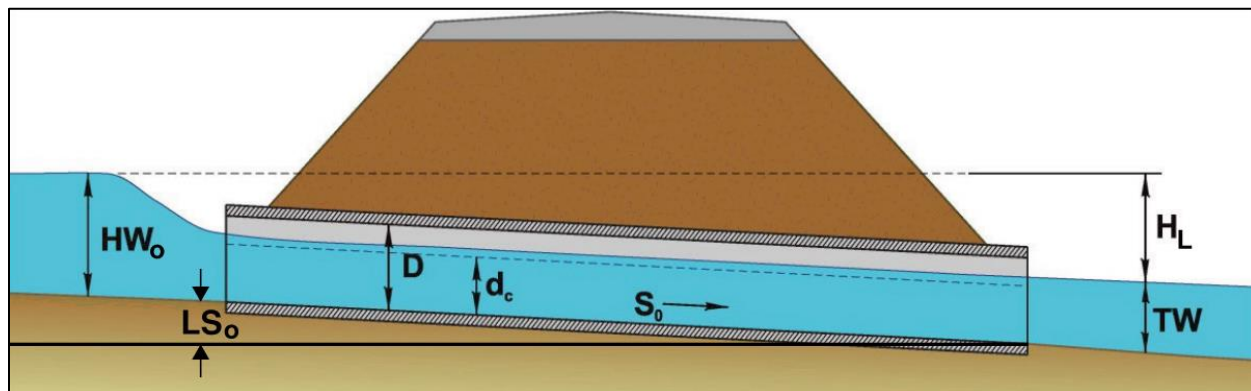


Figure 5-15. Open Channel Flow when $TW > d_c$ (FHWA HDS 5, 2012)



5.4.4 Outlet Velocity

Calculate culvert outlet velocities to determine the need for erosion protection at the culvert exit. Culverts usually result in outlet velocities that are higher than the natural stream velocities. These outlet velocities may require flow readjustment or energy dissipation to prevent downstream erosion. If outlet erosion protection is necessary due to high velocity, the flow depths and Froude number are needed for design. Refer to **Section 5.3.4.6** for more information.

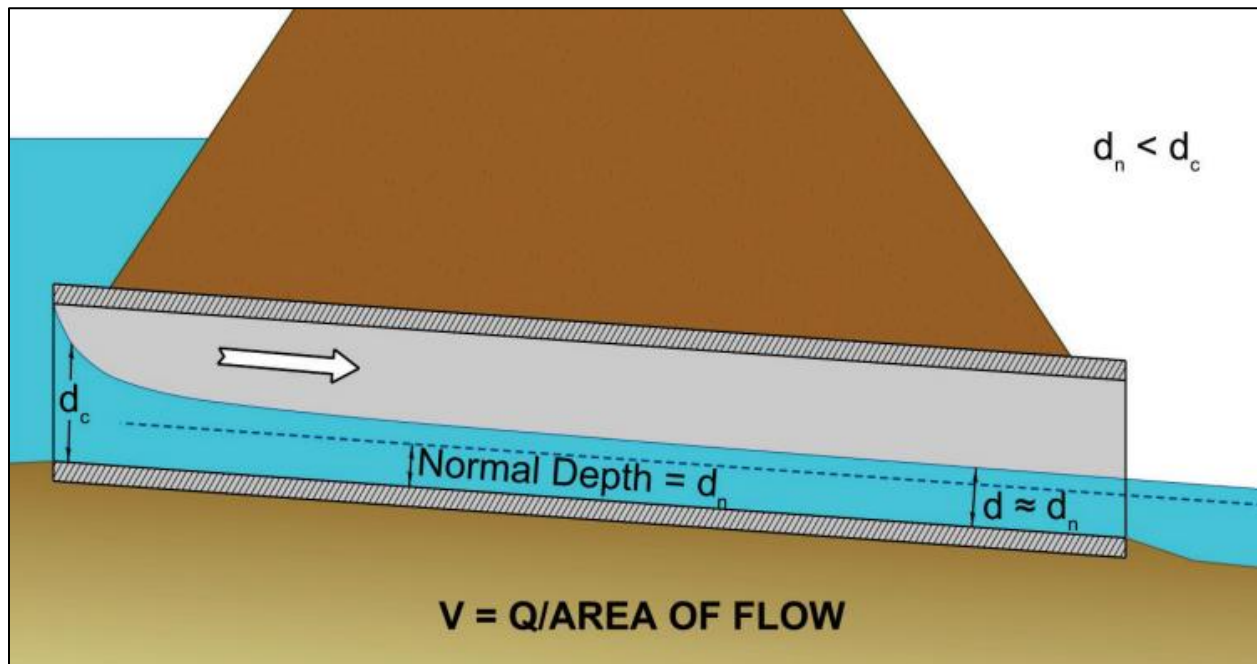
5.4.4.1 Inlet Control

The velocity is calculated from **Equation 5.2** after determining the outlet depth. Use either of the following methods to determine the outlet depth:

- Calculate the water surface profile through the culvert. Begin the computation at d_c at the entrance and proceed downstream to the exit. Determine the depth and flow area at the exit.
- Assume normal depth and velocity. This method is used because the water surface profile converges towards normal depth if the culvert length is adequate. This outlet velocity may be slightly higher than the actual velocity at the outlet. Normal depths, in feet, may be obtained from design aids in publications such as *Design Charts for Open Channel Flow* (FHWA HDS 3, 1973).

Refer to **Figure 5-16** for outlet velocity illustration under inlet control conditions.

Figure 5-16. Outlet Velocity Under Inlet Control (FHWA HDS 5, 2012)



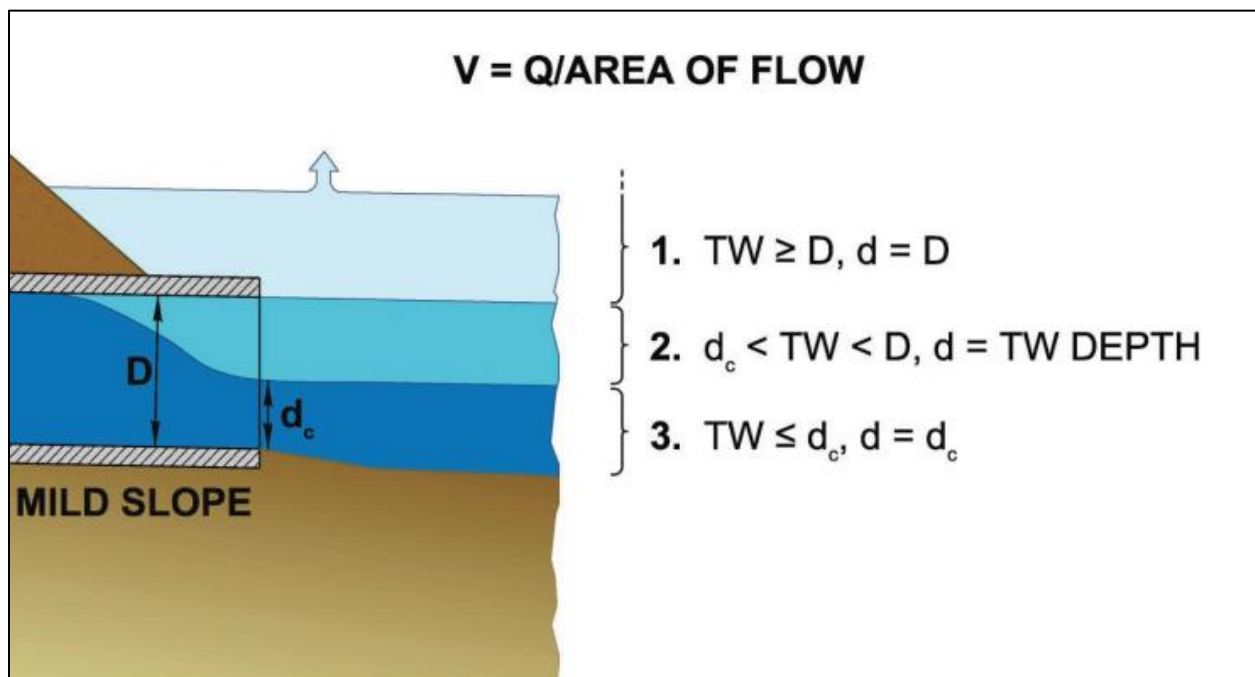
5.4.4.2 Outlet Control

The cross-sectional area of the flow is defined by the geometry of the outlet and either critical depth, tailwater depth, or height of the conduit.

- Critical depth is used when the tailwater is less than critical depth
- Tailwater depth is used when the tailwater is greater than critical depth, but below the top of the barrel
- The total barrel area is used when the tailwater exceeds the top of the barrel

Refer to **Figure 5-17** for outlet velocity illustration under outlet control conditions.

Figure 5-17. Outlet Velocity Under Outlet Control (FHWA HDS 5, 2012)



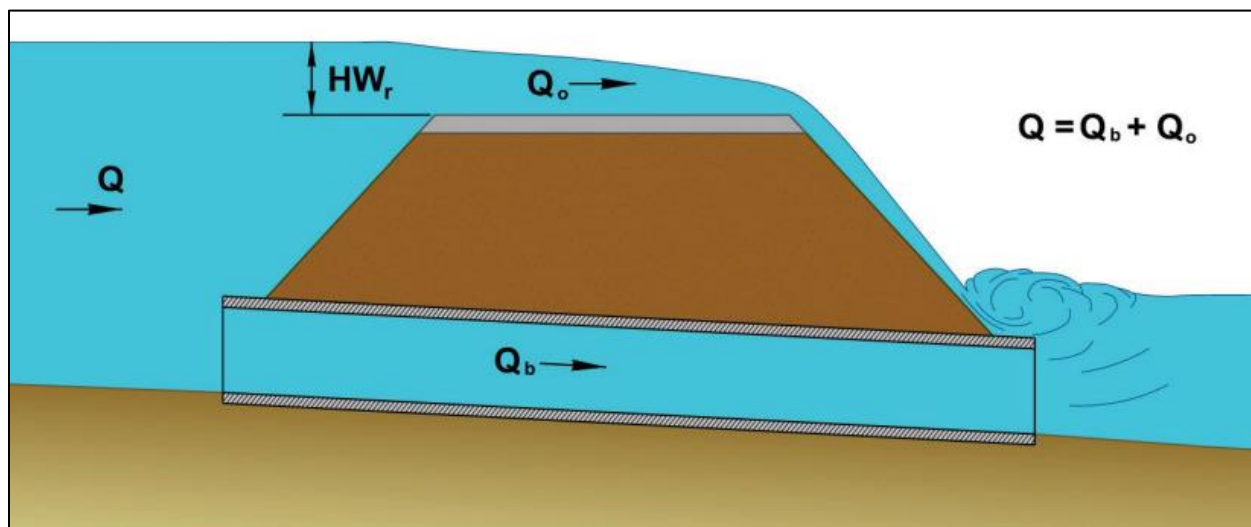
5.4.5 Roadway Overtopping

Roadway overtopping is not considered a part of an MDOT design. However, overtopping is presented in this manual to help with analysis of historical flooding observations.

Roadway overtopping begins when the headwater rises to the elevation of the roadway as shown in **Figure 5-18**. The overtopping often occurs at the low point of a sag vertical curve on the roadway. Roadway overtopping is rarely part of a design. Overtopping is analyzed during a flood event to verify that crossings are properly sized. Do not overtop for the 2% AEP (50-year) storm event. Do not cause harmful interference during the 1% AEP (100-year) storm event. For existing roadways that are overtopped where a grade raise is proposed, check for harmful interference even if no culvert improvements are proposed. Refer to **Section 5.3.2.3** on culvert design criteria and policy on harmful interference.

The roadway overtopping flow is similar to flow over a broad-crested weir as shown in **Equation 5.9**. In situations where sloping roadways are overtopped, the roadway is considered a sloped weir. Refer to Chapter 8, Stormwater Storage Facilities for Flood Control, Section 8.6.3 for a discussion on sloped weirs. Flow coefficients for flow overtopping roadway embankments are found in FHWA HDS 5 (2012) as well as in the documentation of FHWA HY-8 Culvert Hydraulic Analysis Program.

Figure 5-18. Roadway Overtopping (FHWA HDS 5, 2012)

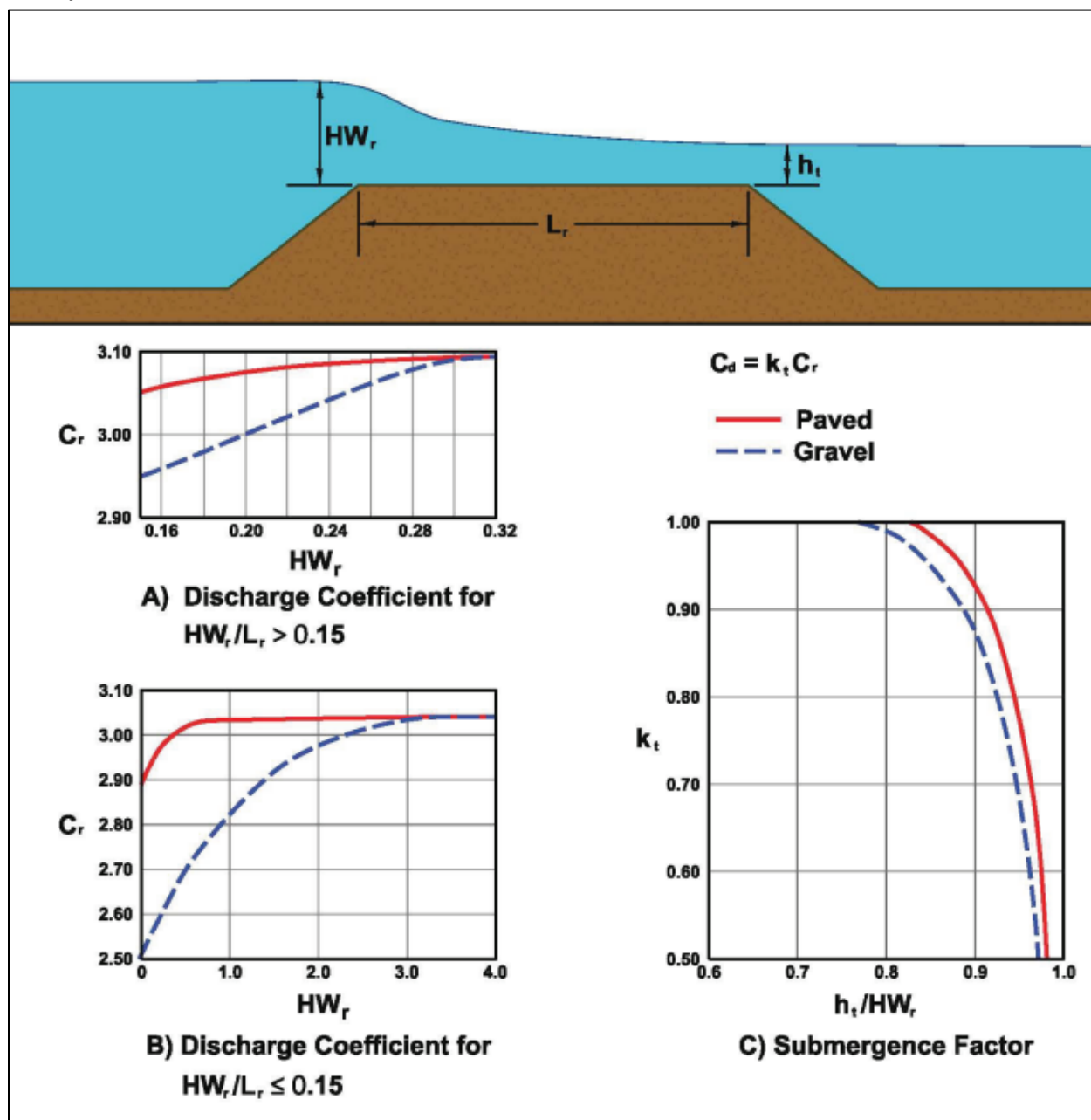


$$Q_o = C_d L_r HW_r^{1.5} \quad (5.9)$$

Where:

- Q_o = overtopping flow rate, cfs
- C_d = overtopping discharge coefficient (weir coefficient) = $k_t C_r$
- k_t = submergence coefficient (refer to **Figure 5-19**)
- C_r = discharge coefficient (refer to **Figure 5-19**)
- L_r = length of the roadway crest, ft
- HW_r = upstream depth, measured above the roadway crest, ft

Figure 5-19. Discharge Coefficients for Roadway Overtopping (FHWA HDS 5, 2012)



5.4.5.1 Length

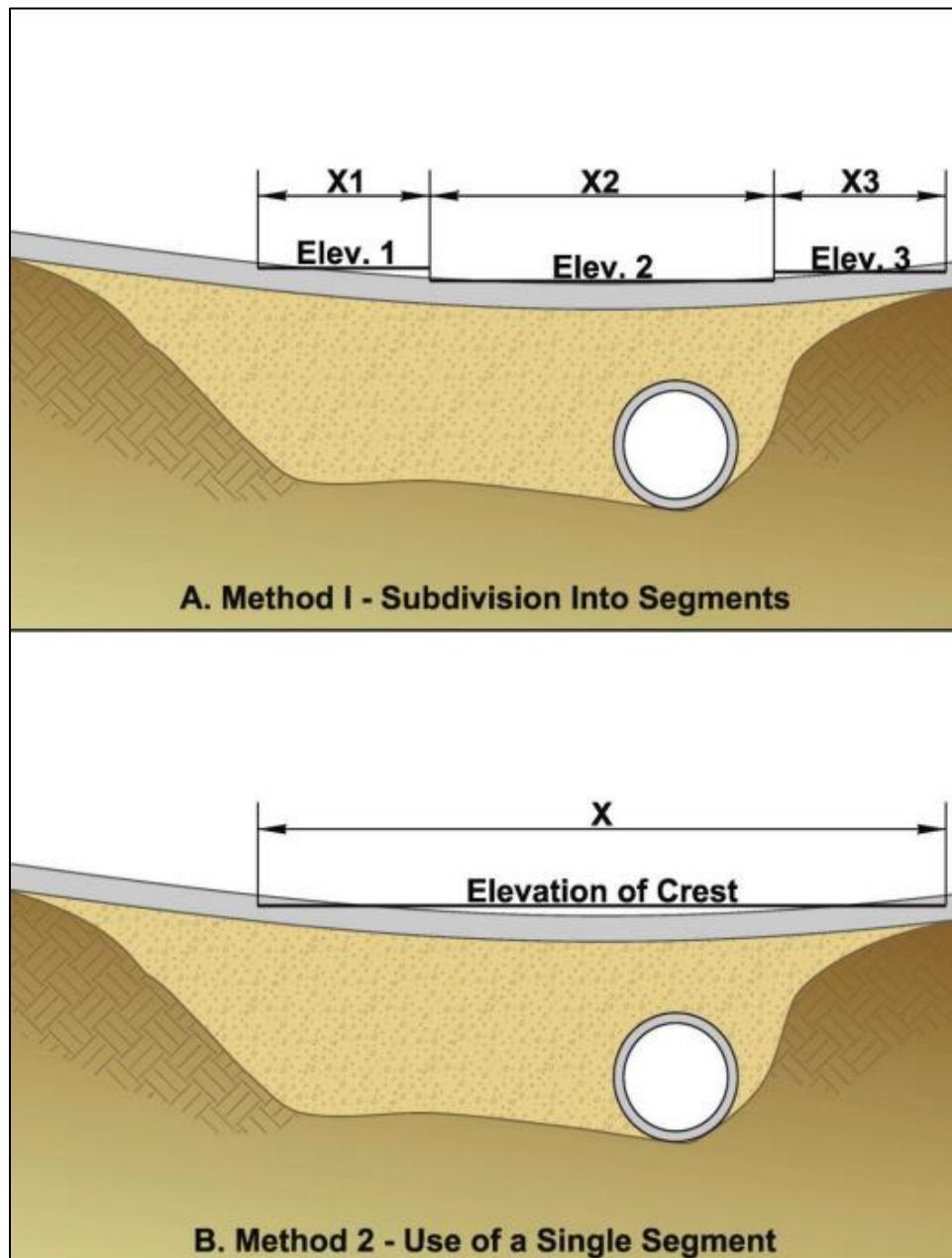
The overtopping length is difficult to determine when the crest is defined by a roadway sag vertical curve. The overtopping length can be determined using one of the following two methods:

- Method 1: Recommend subdividing the roadway into a series of segments. The flow over each segment is calculated for a given headwater. The flows for each segment are summed to determine the total flow.

- Method 2: The length can be represented by a single horizontal line (one segment). The length of the weir is the horizontal length of this segment. The depth is the average depth (area/length) of the upstream pool above the roadway.

Refer to **Figure 5-20** for examples of how to use segments to determine the weir crest length of a roadway sag vertical curve.

Figure 5-20. Weir Crest Length Determinations for Roadway Overtopping (FHWA HDS 5, 2012)



5.4.5.2 Total Flow

Total flow is calculated for a given upstream water surface elevation using **Equation 5.9**. Consider the following when calculating total flow:

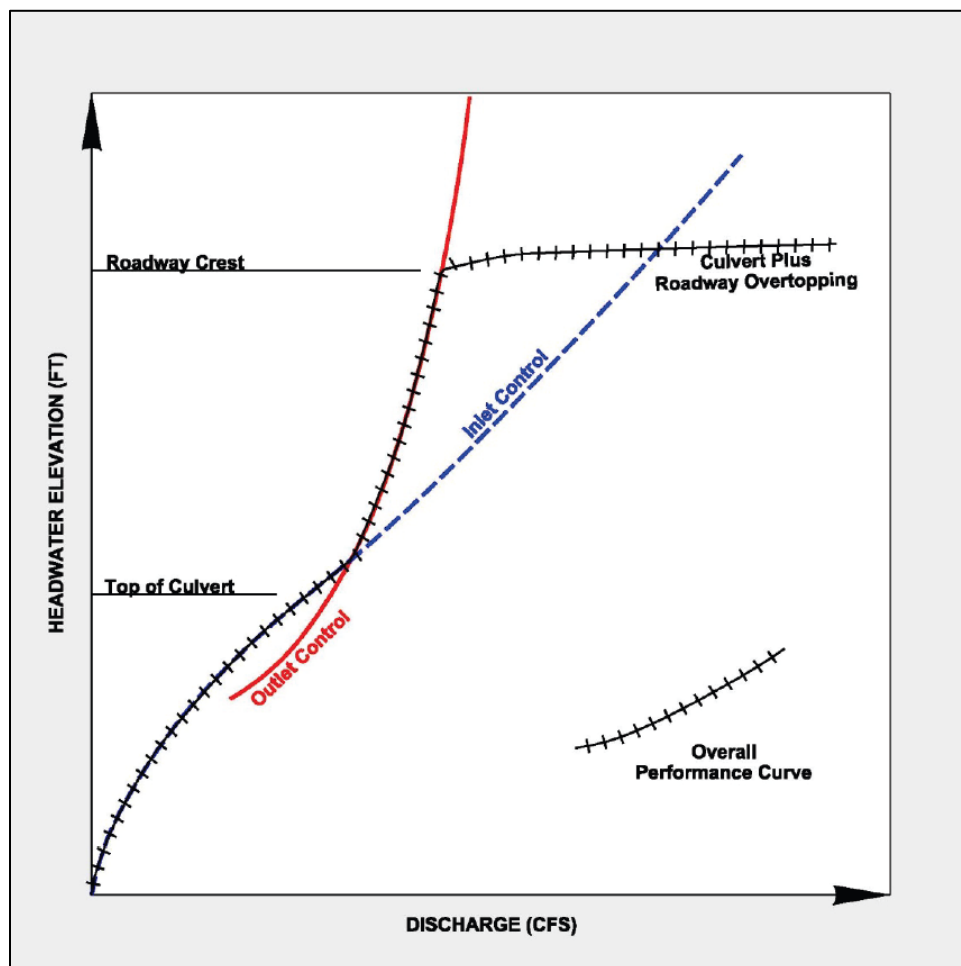
- Roadway overflow plus culvert flow equals total design flow
- A trial-and-error process is necessary to determine the amount of flow through the culvert and across the roadway
- Performance curves for the culvert and the road overflow are summed to yield an overall performance curve
- An alternate approach is given in Chapter 4, Open Channels and Roadside Ditches, Section 4.4.3

5.4.6 Performance Curves

Performance curves are plots of flow rate vs. headwater depth or elevation. The culvert performance curve is made up of the controlling portions of the individual performance curves for each of the following control sections as shown in **Figure 5-21** and described in this section.

- Inlet Performance Curve - Developed using either the inlet control equations or nomographs (refer to FHWA HDS 5, 2012)
- Outlet Performance Curve - Developed using **Equations 5.1** through **5.7**, the outlet control nomographs (refer to FHWA HDS 5 (2012), or backwater calculations)
- Roadway Performance Curve - Developed using **Equation 5.9**.
- Overall Performance Curve – Sum the amount of flow through the culvert and across the roadway by performing the following steps:
 - Select a range of flow rates and determine the corresponding headwater elevations for the culvert flow alone. These flow rates should fall above and below the design discharge and cover the entire flow range of interest. Calculate both inlet and outlet control headwaters.
 - Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.
 - When the culvert headwater elevations exceed the roadway crest elevation, overtopping will begin. Calculate the upstream water surface depth above the roadway for each selected flow rate. Use the water surface depths and **Equation 5.9** to calculate flow rates across the roadway.
 - Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve as shown in **Figure 5-21**.

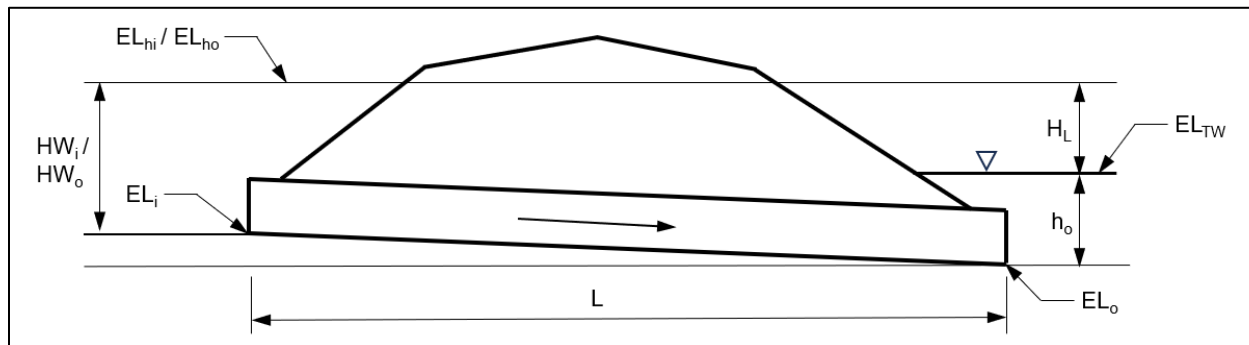
Figure 5-21. Overall Performance Curve (FHWA HDS 5, 2012)



5.4.7 Culvert Design Procedure

Design culverts for a constant discharge, considering inlet and outlet control, by using the following procedure. The equations in **Section 5.4** are used in this procedure. Following the design method without understanding culvert hydraulics and the equations in **Section 5.4** can result in an inadequate, unsafe, or costly structure.

The Culvert Design Form is provided in **Appendix 5-B**, Figure 5-B-2 and the Culvert Design Flow Chart is provided in **Appendix 5-E** to guide the user through design. The design form contains cells for the project description, designer's identification, hydrologic data, culvert dimensions and elevations, trial culvert description, inlet and outlet control headwater, culvert barrel selected, and comments. The flow chart guides the engineer through the hydraulic analysis of existing and proposed culverts. Elevation datum of variables used in the culvert design procedure are defined in **Figure 5-22**.

Figure 5-22. Culvert Headwater Elevation Definitions

HW_i = Headwater height at inlet section, culvert in inlet control. Height based off inlet invert.

HW_o = Headwater height at inlet section, culvert in outlet control. Height based off inlet invert.

EL_{hi} = Headwater elevation at inlet section, culvert in inlet control. Elevation based project elevation datum.

EL_{ho} = Headwater elevation at inlet section, culvert in outlet control. Elevation based project elevation datum.

EL_i = Invert elevation at inlet section, based project elevation datum.

EL_o = Invert elevation at outlet section, based project elevation datum.

EL_{TW} = Tailwater elevation, based project elevation datum.

H_L = Total Energy loss through culvert.

h_o = Larger of TW or $(d_c + D)/2$.

Step 1 Assemble site data and project file

A. The minimum data required are:

- USGS, site, and location maps with accurate topographic information
- Elevation products (3DEP), including 1 meter DEM (if available)
<https://apps.nationalmap.gov/downloader/#/>
- Embankment cross-section
- Roadway profile
- Hydraulic survey - refer to link:
[Chapter 4 - Survey - Section 4.5 Hydraulic Survey](#)
- Photographs
- Field visit estimate (sediment, debris potential)
- Design data at nearby structures

- B. Studies by other agencies including:
 - a. Small dams - NRCS, USACE, BLM
 - b. Canals - NRCS, USACE, USBR
 - c. Floodplain - NRCS, USACE, FEMA, USGS, NOAA
 - d. Storm drain - local or private
- C. Environmental constraints:
 - e. Commitments contained in review documents
 - f. Fish migration
 - g. Wildlife passage
- D. Design criteria:
 - h. Review **Section 5.3.2.3** for applicable criteria
 - i. Prepare risk assessment or analysis. Evaluate key design parameters for the project location and highlight important risk elements to address in the overall design.

Step 2 Determine hydrology

- A. Refer to Chapter 3, Hydrology
- B. Determine extent of the drainage area. If more than 2 square miles, request design flows from the Hydraulic Unit Supervisor. If less than 2 square miles, calculate peak flow.
- C. Determine flood frequency from criteria in **Table 5-1**.

Step 3 Determine tailwater (TW)

- A. Refer to Chapter 4, Open Channels and Roadside Ditches
- B. Minimum downstream channel data required are a cross-section and the rating curve.
- C. Calculate the TW using the design flow rate and normal depth (single section) or using a water surface profile.
 - a. Calculate d_c using appropriate charts in FHWA HDS 5 (2012) or FHWA software: Hydraulic Toolbox or HY-8.
 - i. Locate flow rate and determine d_c : d_c cannot exceed D .
 - ii. If $d_c > 0.9D$, consult Brater and King (1976) for a more accurate d_c , if needed, since curves are truncated where they converge.
 - b. Calculate $(d_c + D)/2$.
 - c. Determine (h_o) .
 - i. h_o = the larger of TW or $(d_c + D/2)$.

Step 4 Analyze culvert using FHWA HY-8 or nomograph procedure

- A. For FHWA HY-8, refer to HY-8 User Manual for software details

- B. For nomograph procedure, determine the inlet control headwater depth (HW_i) for the existing culvert using the inlet control nomograph (refer to FHWA HDS 5, 2012)
- Locate the size or height on the scale
 - Locate the discharge
 - For a circular shape use discharge
 - For a box shape use discharge per foot of span
 - Locate headwater to diameter ratio
 - Use a straightedge
 - Extend a straight line from the culvert size through the flow rate
 - Mark the first HW/D scale. Extend a horizontal line to the desired scale and read HW/D and note on Culvert Design Form in **Appendix 5-B**.
 - Calculate headwater depth (HW_i)
 - Multiply HW/D by D to obtain HW to energy grade line
 - Neglect the approach velocity HW_i = HW
 - Include the approach velocity HW_i = HW - approach velocity head
 - EL_{hi} = HW_i + EL_i

Step 5 Determine Outlet Control Headwater Depth at Inlet (HW_o) for Existing Culvert

- Use tailwater (TW) calculated in Step 3
- Determine (K_e)
 - Entrance loss coefficient from Table 5-B-2 in **Appendix 5-B**
- Determine losses through the culvert barrel (H_L)
 - Use **Equation 5.5**. Use Chapter 7, Inlet and Enclosed Storm Drainage Systems, Figure 7-8, Values of Hydraulic Elements of Circular Section for Various Depths of Flow, to compute barrel area (A) and hydraulic radius (R) if the tailwater is below the culvert crown. Nomographs (FHWA HDS 5, 2012) can be used if the tailwater is above the culvert crown.
 - Locate appropriate K_e scale
 - Compute outlet velocity, V_o, based on barrel area at tailwater depth
 - If using nomographs, locate culvert length (L) or (L₁). Do not use nomographs if tailwater is below the culvert crown.
 - Use (L) if Manning's n matches the n value of the culvert and
 - Use (L₁) to adjust for a different culvert n value.

$$L_1 = L \left(\frac{n_1}{n} \right)^2 \quad (5.10)$$

Where:

L₁ = adjusted culvert length, feet
 L = actual culvert length, feet
 N₁ = desired Manning's n value
 n = Manning's n value on chart

- a. Mark point on turning line
 - i. Use a straightedge
 - ii. Connect size with length
- b. Read H
 - i. Use a straightedge
 - ii. Connect Q and turning point
 - iii. Read H on Head Loss scale

D. Calculate outlet control headwater HW_o

- c. Use **Equation 5.11**, if V_u and V_d are neglected:

$$HW_o = H_L + h_o + EL_o - EL_i \quad (5.11)$$

- d. Use **Equations 5.1**, **5.4c**, and **5.6** to include V_u and V_d
- e. If HW_o is less than $1.2D$ and control is outlet control
 - i. The barrel may flow partly full
 - ii. The approximate method of using the greater of tailwater or $(d_c + D)/2$ may not be applicable
 - iii. Backwater calculations should be used to check the result
 - iv. If the headwater depth falls below $0.75D$, utilize FHWA HY-8 to compute HW_o

Step 6 Determine controlling headwater (HW_c) for existing culvert

- A. Compare HW_i and HW_o and use the higher value
- B. $HW_c = HW_i$, if $HW_i > HW_o$ retained for future reference as provided for in documentation
- C. Compare HW_c to HW_a (allowable headwater)

Step 7 Compute discharge over the roadway (Q_o) for existing culvert (if applicable)

- A. Calculate depth above the roadway (HW_r)
 - a. $HW_r = HW_c - HW_{ov}$
 - b. HW_{ov} = height of roadway crest above inlet invert
- B. If $HW_r = 0$, $Q_o = 0$
 - a. If $HW_r > 0$, determine C_d from FHWA HDS 5 (2012)
- C. Determine length of roadway crest, L
- D. Calculate Q_o using **Equation 5.12**:

$$Q_o = C_d L HW_r^{1.5} \quad (5.12)$$

Step 8 Compute total discharge, Q_t , using **Equation 5.13**:

$$Q_t = Q_b + Q_o \quad (5.13)$$

Step 9 Calculate outlet velocity (V_o) and depth (d_n)

- A. If inlet control is the controlling headwater
 - a. Calculate flow depth at culvert exit
 - i. Use normal depth (d_n) or water surface profile
 - b. Calculate flow area (A)
 - c. Calculate exit velocity (V_o) = Q/A
- B. If outlet control is the controlling headwater
 - a. Calculate flow depth at culvert exit
 - i. Use (d_c) if $d_c > TW$
 - ii. Use (TW) if $d_c < TW < D$
 - iii. Use (D) if $D < TW$
 - b. Calculate flow area (A)
 - c. Calculate exit velocity (V_o) = Q/A

Step 10 Select design alternative

- A. Refer to **Section 5.3.4** for culvert design features
- B. Choose trial culvert material, shape, size, and entrance type

Step 11 Repeat steps 5 through 10 for design alternative(s)

Step 12 Summarize existing data

- A. Summarize in Culvert Design Form in Figure 5-B-2 provided in **Appendix 5-B** (or other means).

Step 13 Review results to confirm

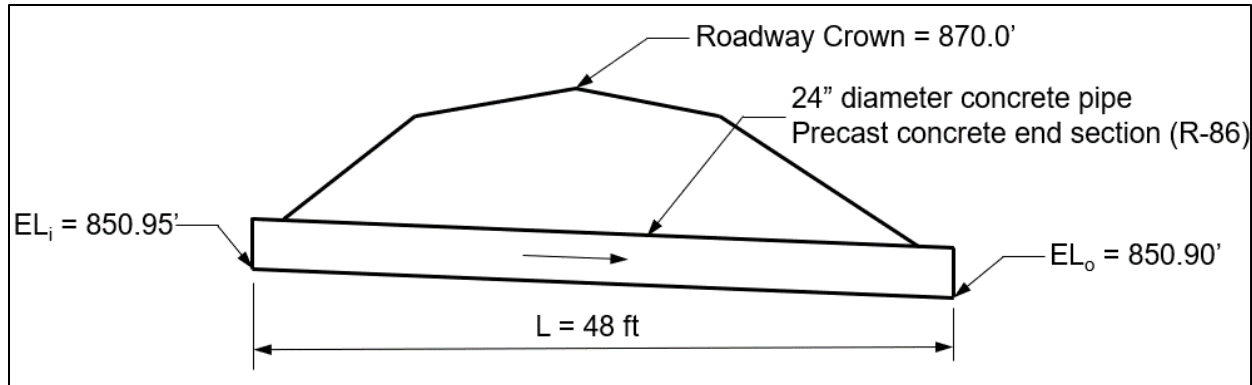
- A. Barrel has adequate cover
- B. Culvert size and length are adequate to fit within roadway embankment.
- C. Wingwalls and headwalls fit site constraints
- D. Invert placement is proper
- E. Outlet velocity requirements are met
- F. Allowable headwater criteria is not exceeded
- G. Allowable overtopping criteria is not exceeded

H. No harmful interference is created

5.4.8 Example Problem

The following example problem relates to Figure 5-23 **Figure 5-23** and follows the Design Procedure Steps described in **Section 5.4.7**.

Figure 5-23. Example Roadway Cross-Section Showing Existing Culvert



Step 1 Assemble Site Data and Project File

- Site survey project file contains:
 - USGS, site and location maps
 - Hydraulic survey (refer to data in Step 3)
 - Roadway profile
 - Check drainage area
- Site notes indicate:
 - Minor arterial with ADT > 3000 VPD
 - No sediment or debris problems
 - No nearby structures
 - Culvert is at low point of roadway profile
 - Low edge of shoulder (Assuming 14 ft @ 0.02 feet/foot cross slope = 869.72 feet)
- Studies by other agencies – none
- Environmental risk assessment shows:
 - No building near floodplain
 - No sensitive floodplain values
 - No FEMA involvement
- Design criteria: (Per **Table 5-1**)
 - 2% AEP (50-year) frequency for design
 - 1% AEP (100-year) frequency for check

Step 2 Determine Hydrology

- Design, $Q_{2\%} = 40$ cfs
- Check, $Q_{1\%} = 50$ cfs

Step 3 Determine Tailwater

Cross-section of channel (Slope = 0.002 feet/foot)

Point	Station, ft	Elevation, ft	Manning's n
1	0.0	855.0	0.08
2	10.0	854.0	0.04
3	15.0	851.0	0.04
4	16.0	850.9	0.04
5	17.0	850.9	0.04
6	18.0	851.0	0.04
7	23.0	854.0	0.08
8	33.0	855.0	0.08

Use FHWA Hydraulic Toolbox to calculate the tailwater for design ($Q_{2\%} = 40$ cfs) and check ($Q_{1\%} = 50$ cfs) flows. First, input the cross-section in the software as shown in **Figure 5-24**. Then, determine the tailwater for the design and check flows using the channel analysis tool as shown in **Figure 5-25** and **Figure 5-26**.

Figure 5-24. Hydraulic Toolbox – TW Channel Information

User-Defined Cross Section

Channel File

Browse for Existing .TW File

Channel

Slope of Channel: ft/ft

Number of Cross-sec Points:

Irregular Channel Cross-Section

No.	Station (ft)	Elevation (ft)	Manning n
1	0.000	855.000	0.0800
2	10.000	854.000	0.0400
3	15.000	851.000	0.0400
4	16.000	850.900	0.0400
5	17.000	850.900	0.0400
6	18.000	851.000	0.0400
7	23.000	854.000	0.0800
8	33.000	855.000	

Figure 5-25. Hydraulic Toolbox – Q_{2%} TW Depth

Channel Analysis

Type: **Cross Section** Define...

Side Slope 1 (Z1): 0.0 H : 1V

Side Slope 2 (Z2): 0.0 H : 1V

Channel Width (B): 0.0 (ft)

Pipe Diameter (D): 0.0 (ft)

Longitudinal Slope: 0.002 (ft/ft)

☐ Override Default

Manning's Roughness: 0.0400

☐ Use Lining

Lining Type: Woven Paper Net

☒ Enter Flow: 40.000 (cfs)

☐ Enter Depth: 2.659 (ft)

Calculate

Plot... Compute Curves...

OK Cancel

Parameter	Value	Units
Flow	40.000	cfs
Depth	2.659	ft
Area of Flow	18.792	sq ft
Wetted Perimeter	12.958	ft
Hydraulic Radius	1.450	ft
Average Velocity	2.129	fps
Top Width (T)	11.530	ft
Froude Number	0.294	
Critical Depth	1.436	ft
Critical Velocity	5.570	fps
Critical Slope	0.02684	ft/ft
Critical Top Width	7.453	ft
Max Shear Stress	0.332	lb/ft ²
Avg Shear Stress	0.181	lb/ft ²
Composite Manning's n Equ...	Lotter ...	
Manning's Roughness	0.0400	

Figure 5-26. Hydraulic Toolbox – Q_{1%} TW Depth

Channel Analysis

Type: **Cross Section** Define...

Side Slope 1 (Z1): 0.0 H : 1V

Side Slope 2 (Z2): 0.0 H : 1V

Channel Width (B): 0.0 (ft)

Pipe Diameter (D): 0.0 (ft)

Longitudinal Slope: 0.002 (ft/ft)

☐ Override Default

Manning's Roughness: 0.0400

☐ Use Lining

Lining Type: Woven Paper Net

☒ Enter Flow: 50.000 (cfs)

☐ Enter Depth: 2.943 (ft)

Calculate

Plot... Compute Curves...

OK Cancel

Parameter	Value	Units
Flow	50.000	cfs
Depth	2.943	ft
Area of Flow	22.197	sq ft
Wetted Perimeter	14.061	ft
Hydraulic Radius	1.579	ft
Average Velocity	2.253	fps
Top Width (T)	12.476	ft
Froude Number	0.298	
Critical Depth	1.612	ft
Critical Velocity	5.850	fps
Critical Slope	0.02613	ft/ft
Critical Top Width	8.040	ft
Max Shear Stress	0.367	lb/ft ²
Avg Shear Stress	0.197	lb/ft ²
Composite Manning's n Equ...	Lotter ...	
Manning's Roughness	0.0400	

Compute the average of critical depth (d_c) and barrel diameter (D):

For $Q_{2\%} = 40$ cfs:

From **Figure 5-27** Chart 4B (green line), critical depth = 2 ft

$$(d_c + D)/2 = (2 + 2)/2 = 2.0 \text{ ft}$$

For $Q_{1\%} = 50$ cfs:

From **Figure 5-27** Chart 4B (red line), critical depth = 2 ft

$$(d_c + D)/2 = (2 + 2)/2 = 2.0 \text{ ft}$$

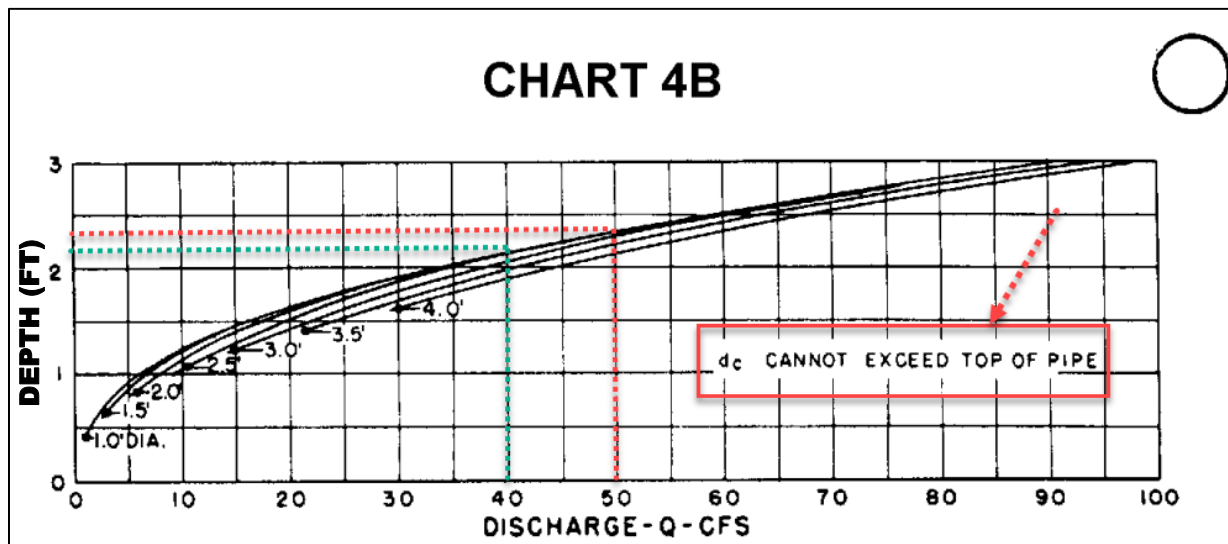
For both flow rates, the computed tailwater is greater than the average of critical depth and barrel diameter. Therefore, $h_0 = \text{TW}$.

The elevation of the TW is:

$$\text{EL}_{\text{TW}2\%} = h_0 = \text{EL}_i + 2.66 \text{ ft} = 850.9 \text{ ft} + 2.66 \text{ ft} = \mathbf{853.56 \text{ ft}}$$

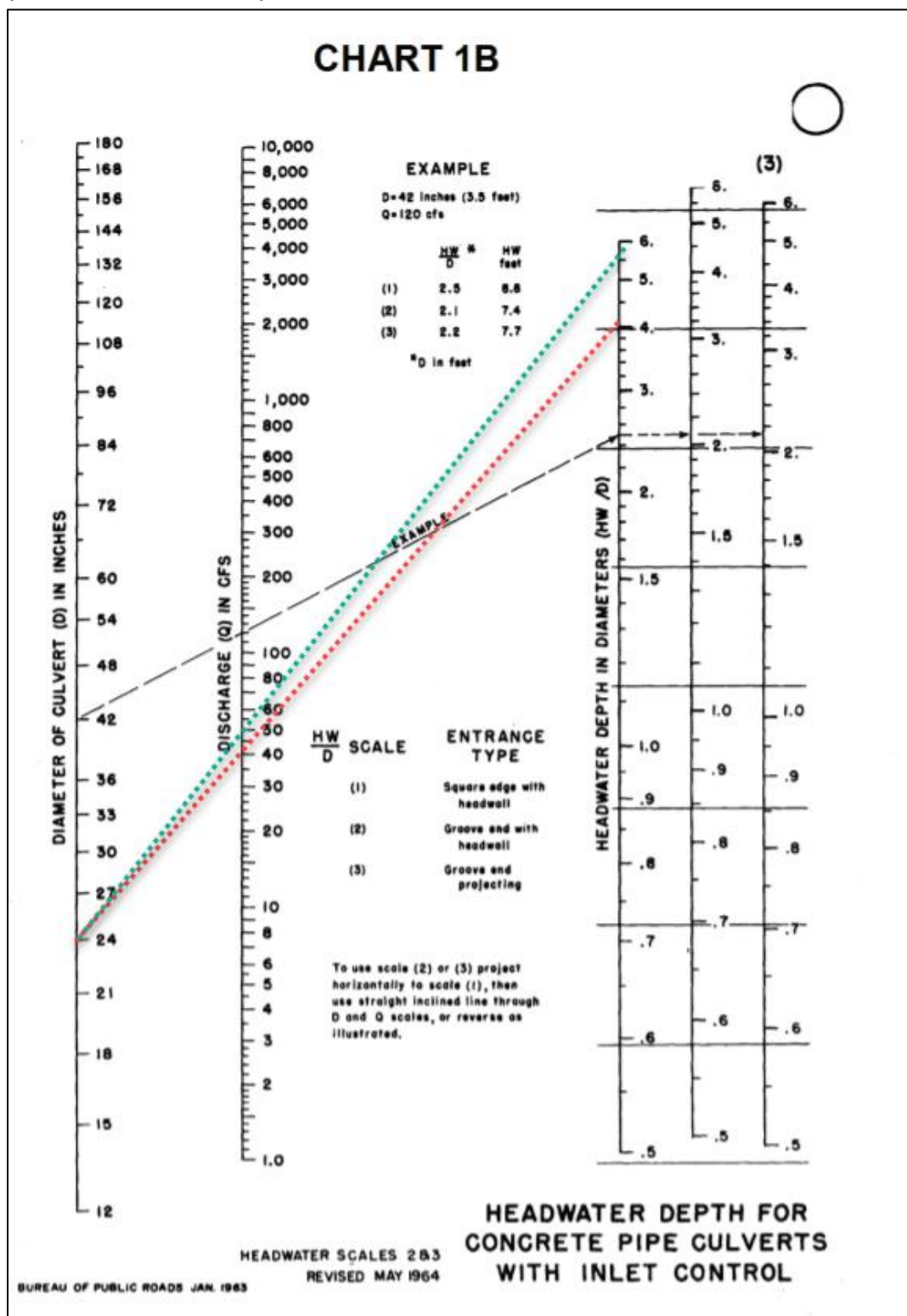
$$\text{EL}_{\text{TW}1\%} = h_0 = \text{EL}_o + 2.94 \text{ ft} = 850.9 \text{ ft} + 2.94 \text{ ft} = \mathbf{853.84 \text{ ft}}$$

Figure 5-27. Chart 4B, Critical Depth Circular Pipe (FHWA HDS 5, 2012)



Step 4 Determine Inlet Control Headwater Depth (HW_i) for Existing Culvert

Figure 5-28. Chart 1B, Headwater Depth for Concrete Culverts with Inlet Control (FHWA HDS 5, 2012)



For $Q_{2\%} = 40$ cfs:

From **Figure 5-28**, Chart 1B (red line), $HW_i/D = 4$ HW_i

$$= 4 \times D = 4 \times 2 \text{ ft} = 8.0 \text{ ft}$$

For $Q_{1\%} = 50$ cfs:

From **Figure 5-28**, Chart 1B (green line), $HW_i/D = 5.9$ HW_i

$$= 5.9 \times D = 5.9 \times 2 \text{ ft} = 11.8 \text{ ft}$$

The elevation of the HW_i is:

$$EL_{hi} = 8.0 \text{ ft} + EL_i = 8.0 \text{ ft} + 850.95 \text{ ft} = \mathbf{858.95 \text{ ft}}$$

$$EL_{hi} = 11.8 \text{ ft} + EL_i = 11.8 \text{ ft} + 850.95 \text{ ft} = \mathbf{862.75 \text{ ft}}$$

Step 5 Determine Outlet Control Headwater Depth at Inlet (HW_o) for Existing Culvert

Tailwater from Step 3:

$$EL_{TW2\%} = 853.56 \text{ ft}$$

$$EL_{TW1\%} = 854.84 \text{ ft}$$

$K_e = 0.5$ (square edge with headwall)

Determine head loss (H_L) using **Equation 5.5**:

$$H_L = \left[K_e + 1 + \left(\frac{29n^2L}{R^{1.33}} \right) \right] \left[\frac{V^2}{2g} \right]$$

Since the tailwater is above the culvert crown, use full barrel area and hydraulic radius to determine outlet velocity and head loss:

$$n = 0.012 \text{ (concrete pipe)}$$

$$\text{Area, } A = (\pi * D^2) / 4 = (\pi * (2 \text{ ft})^2) / 4 = 3.14 \text{ sft}$$

$$\text{Wetted Perimeter, } P = \pi * D$$

$$\text{Hydraulic radius, } R = \text{Area} / \text{Wetted Perimeter, } P$$

$$= ((\pi * D^2) / 4) / (\pi * D)$$

$$= D / 4$$

$$= 2 \text{ ft} / 4 = \mathbf{0.5 \text{ ft}}$$

Determine head loss for $Q_{2\%}$ (40 cfs):

$$\text{Velocity, } V = Q / A = 40 \text{ cfs} / 3.14 \text{ sft} = 12.74 \text{ fps}$$

$$H_L = \left(1 + 0.5 + \frac{29 \cdot (0.012)^2 \cdot 48 \text{ ft}}{(0.5 \text{ ft})^{1.33}} \right) \left(\frac{(12.74 \text{ fps})^2}{2 \cdot 32.2 \text{ ft/s}^2} \right)$$

$$H_L = \underline{5.05 \text{ feet}}$$

Determine head loss for $Q_{1\%}$ (50 cfs):

$$\text{Velocity, } V = Q / A = 50 \text{ cfs} / 3.14 \text{ sft} = 15.92 \text{ fps}$$

$$H_L = \left(1 + 0.5 + \frac{29 \cdot (0.012)^2 \cdot 48 \text{ ft}}{(0.5 \text{ ft})^{1.33}} \right) \left(\frac{(15.92 \text{ fps})^2}{2 \cdot 32.2 \text{ ft/s}^2} \right)$$

$$H_L = \underline{7.89 \text{ ft}}$$

Determine outlet control headwater, HW_o

Using **Equation 5.11**:

$$H_o = H_L + h_o + EL_o - EL_i$$

2% AEP (50-year):

$$HW_o = 5.05 \text{ ft} + 2.66 \text{ ft} + 850.90 \text{ ft} - 850.95 \text{ ft} = 7.66 \text{ ft}$$

$$EL_{ho} = HW_o + EL_i = 7.66 \text{ ft} + 850.95 \text{ ft} = \mathbf{858.61 \text{ ft}}$$

1% AEP (100-year):

$$HW_o = 7.89 \text{ ft} + 2.94 \text{ ft} + 850.90 \text{ ft} - 850.95 \text{ ft} = 10.78 \text{ ft}$$

$$EL_{ho} = HW_o + EL_i = 10.78 \text{ ft} + 850.95 \text{ ft} = \mathbf{861.73 \text{ ft}}$$

Step 6 Determine Controlling Headwater (HW_o/EL_c) for Existing Culvert

2% AEP (50-year):

$$HW_i > HW_o; 8.00 \text{ ft} > 7.66 \text{ ft}$$

$$EL_c = 850.95 \text{ ft} + 8.00 \text{ ft} = \mathbf{858.95 \text{ ft (inlet control)}}$$

1% AEP (100-year):

$$HW_i > HW_o; 11.80 \text{ ft} > 10.78 \text{ ft}$$

$$EL_c = 850.95 \text{ ft} + 11.80 \text{ ft} = \mathbf{862.75 \text{ ft (inlet control)}}$$

Compare to Maximum Allowable Headwater (**Section 5.3.4.2**)

Low edge of shoulder: 869.72 ft (OK > 1.5 ft below)

Step 7 Compute Discharge over the Roadway (Q_o), for Existing Culvert

Not applicable since HW_c/EL_c does not exceed roadway elevation.

Step 8 Compute Total Discharge (Q_t)

Not applicable since HW_c/EL_c does not exceed roadway elevation.

Step 9 Calculate Outlet Velocity (V_o)

Determined in Step 6:

$$V_o (2\%) = 12.74 \text{ fps}$$

$$V_o (1\%) = 15.92 \text{ fps}$$

Step 10 Select Design Alternative

Design requirements from **Section 5.3.4.5** – Outlet Velocity:

Exit velocity must be less than 6 fps

Choose trial size:

Try 42-inch diameter, assume standard end section ($K_e = 0.5$) and same length as existing (48 ft). The proposed inverts are lowered 6 inches to 850.45 ft at the upstream end and 850.40 ft on the downstream end to meet requirements in **Section 5.3.4.7**. (Note: invert recessed depth exceeds required $0.1 \times$ rise)

$$n = 0.024 \text{ (assume CMP)}$$

$$A_{full} = (\pi * D^2) / 4$$

$$= (\pi * (3.5 \text{ ft})^2) / 4 = 9.62 \text{ sft}$$

$$R_{full} = D / 4 = 3.5 \text{ ft} / 4 = 0.875 \text{ ft}$$

For $Q_{2\%}$ (40 cfs), find A_{part} based on TW depth:

$$TW_{2\%} / D = (2.66 \text{ ft} + 0.5 \text{ ft}) / 3.5 \text{ ft} = 0.90$$

(Note: Invert lowered 0.5 ft below stream bottom)

Based on partial elements (**Figure 5-29**):

$$A_{\text{part}}/A_{\text{full}} = 0.95$$

$$A_{\text{part}} = 0.95 * A_{\text{full}} = 0.95 * 9.62 \text{ sft} = 9.14 \text{ sft}$$

$$V_o = Q_{2\%} / A_{\text{part}}$$

$$V_o = 40 \text{ cfs} / 9.14 \text{ sft} = 4.38 \text{ fps} < 6 \text{ fps } \mathbf{OK}$$

Inlet Control (refer to **Figure 5-30**):

$$\text{For } Q_{2\%} = 40 \text{ cfs, } HW_i/D = 0.84$$

$$HW_i = 0.84 * D = 0.84 * 4.0 \text{ ft} = 2.94 \text{ ft}$$

$$\text{For } Q_{1\%} = 50 \text{ cfs, } HW_i/D = 0.97$$

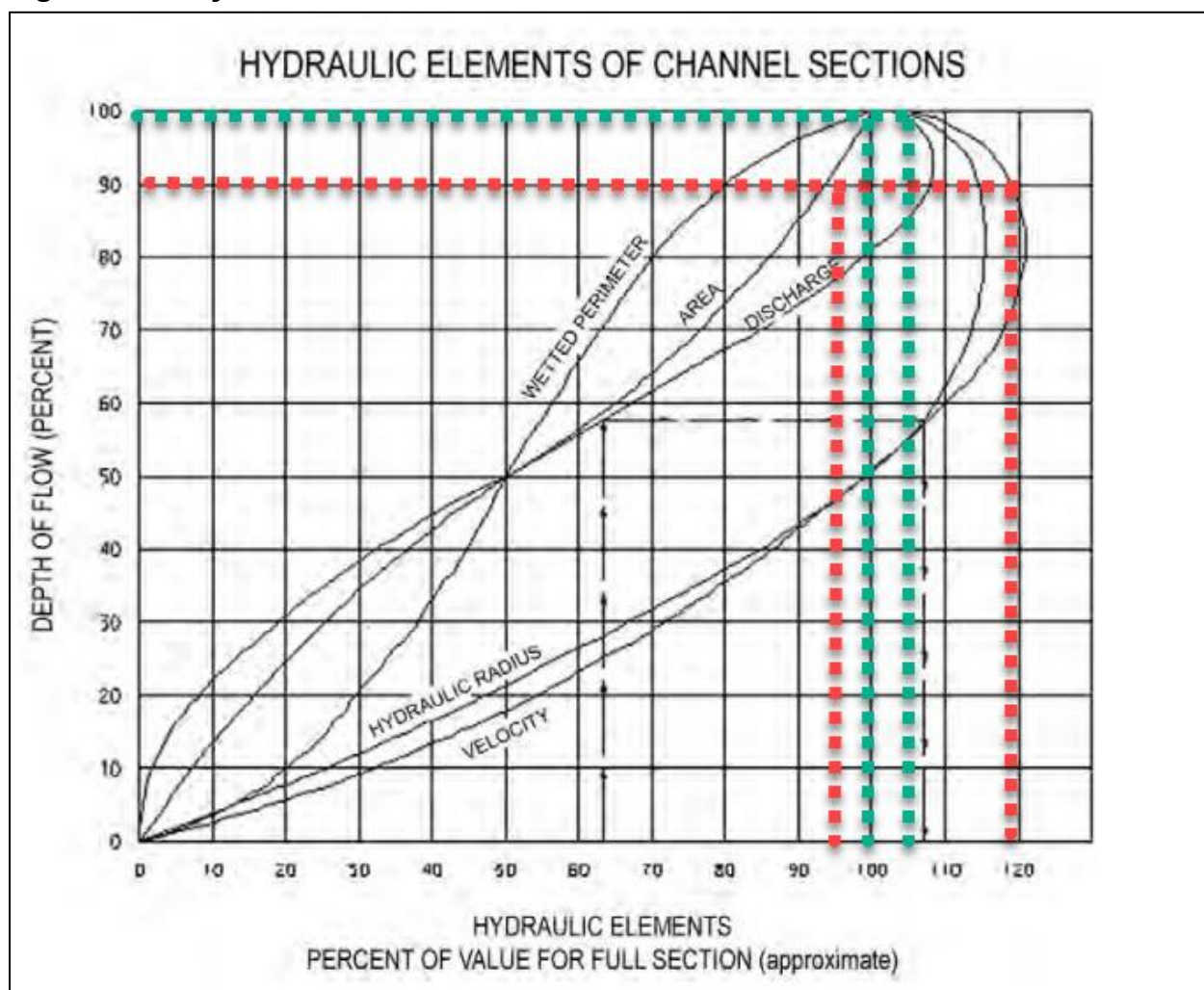
$$HW_i = 0.97 * D = 0.97 * 3.5 \text{ ft} = 3.40 \text{ ft}$$

The elevation of HW_i is:

$$EL_{hi2\%} = 2.94 \text{ ft} + EL_i = 2.94 \text{ ft} + 850.45 \text{ ft} = \mathbf{853.39 \text{ ft}}$$

$$EL_{hi1\%} = 3.40 \text{ ft} + EL_i = 3.40 \text{ ft} + 850.45 \text{ ft} = \mathbf{853.85 \text{ ft}}$$

Figure 5-29. Hydraulic Elements of Channel Sections



Step 11 Repeat Steps 5 through 10 for Design Alternative

Determine inlet control headwater (HW_i/EL_{hi}) (determined in Step 10):

$$Q_{2\%} = 40 \text{ cfs}, HW_i = 2.94 \text{ ft}; EL_{hi} = 853.39 \text{ ft}$$

$$Q_{1\%} = 50 \text{ cfs}, HW_i = 3.40 \text{ ft}; EL_{hi} = 853.85 \text{ ft}$$

Determine outlet control headwater (HW_o)

Determine head loss for $Q_{2\%} = 40$ cfs:

$$V_o = 4.38 \text{ ft/s (determined in Step 10)}$$

$$R_{part} / R_{full} = 1.19 \text{ (Based on 90\% flow depth - refer to Figure 5-29)}$$

$$R_{part} = 1.19 * R_{full} = 1.19 * 0.875 \text{ ft} = 1.04 \text{ ft}$$

$$H_L = \left(1 + K_e + \frac{29n^2L}{R^{1.33}} \right) \left(\frac{V^2}{2g} \right)$$

$$H_L = \left(1 + 0.5 + \frac{29 \cdot (0.024)^2 \cdot 48 \text{ ft}}{(1.04 \text{ ft})^{1.33}} \right) \left(\frac{(4.38 \text{ fps})^2}{2 \cdot 32.2 \text{ ft/s}^2} \right)$$

$$H_L = \underline{0.68 \text{ ft}}$$

Determine head loss for $Q_{1\%} = 50$ cfs:

$$TW_{1\%} / D = (2.94 \text{ ft} + 0.5 \text{ ft}) / 3.5 \text{ ft} = 0.98$$

$$A_{part}/A_{full} = 0.99 \text{ (refer to Figure 5-29)}$$

$$A_{part} = 0.99 * A_{full} = 0.99 * 9.62 \text{ sft} = 9.52 \text{ sft}$$

$$V_o = Q_{1\%} / A_{part}$$

$$V_o = Q_{1\%} / A_{part} = 50 \text{ cfs} / 9.52 \text{ ft} = 5.25 \text{ fps}$$

$$R_{part} / R_{full} = 1.05 \text{ (refer to Figure 5-29)}$$

$$R_{part} = 1.05 * R_{full} = 1.05 * 0.875 \text{ ft} = 0.92 \text{ ft}$$

$$H_L = \left(1 + K_e + \frac{29n^2L}{R^{1.33}} \right) \left(\frac{V^2}{2g} \right)$$

$$H_L = \left(1 + 0.5 + \frac{29 \cdot (0.024)^2 \cdot 48 \text{ ft}}{(0.92 \text{ ft})^{1.33}} \right) \left(\frac{(5.25 \text{ fps})^2}{2 \cdot 32.2 \text{ ft/s}^2} \right)$$

$$H_L = \underline{1.03 \text{ ft}}$$

Determine outlet control headwater (HW_o/EL_{ho}):

Using **Equation 5.11**:

$$HW_o = H_L + h_o + EL_o - EL_i$$

For $Q_{2\%} = 40$ cfs

$$HW_o = 0.68 \text{ ft} + 2.66 \text{ ft} + 0.5 \text{ ft} + 850.40 \text{ ft} - 850.45 \text{ ft} = 3.79 \text{ ft}$$

$$EL_{ho} = HW_o + EL_i = 3.79 \text{ ft} + 850.45 \text{ ft} = \mathbf{854.24 \text{ ft}}$$

For $Q_{2\%} = 50$ cfs

$$HW_o = 1.03 \text{ ft} + 2.94 \text{ ft} + 0.5 \text{ ft} + 850.40 \text{ ft} - 850.45 \text{ ft} = 4.42 \text{ ft}$$

$$EL_{ho} = HW_o + EL_i = 4.42 \text{ ft} + 850.45 \text{ ft} = \mathbf{854.87 \text{ ft}}$$

Determine Controlling Headwater (HW_c/EL_c):

For $Q_{2\%}$

$$HW_o > HW_i; 3.79 \text{ ft} > 2.94 \text{ ft}; HW_c = 3.79 \text{ ft (outlet control)}$$

$$EL_c = 850.45 \text{ ft} + 3.79 \text{ ft} = \mathbf{854.24 \text{ ft (outlet control)}}$$

For $Q_{1\%}$

$$HW_o > HW_i; 4.42 \text{ ft} > 3.40 \text{ ft}; HW_c = 4.42 \text{ ft (outlet control)}$$

$$EL_c = 850.45 \text{ ft} + 4.42 \text{ ft} = \mathbf{854.87 \text{ ft (outlet control)}}$$

Compare to Maximum Allowable Headwater (**Section 5.3.4.2**)

Low edge of shoulder: 869.72 ft (OK > 1.5 ft below)

Step 12 Summarize Results in Culvert Design Form (Example shown in **Figure 5-31**)

FHWA HY-8 Computer Program

5.4.8.1 Overview

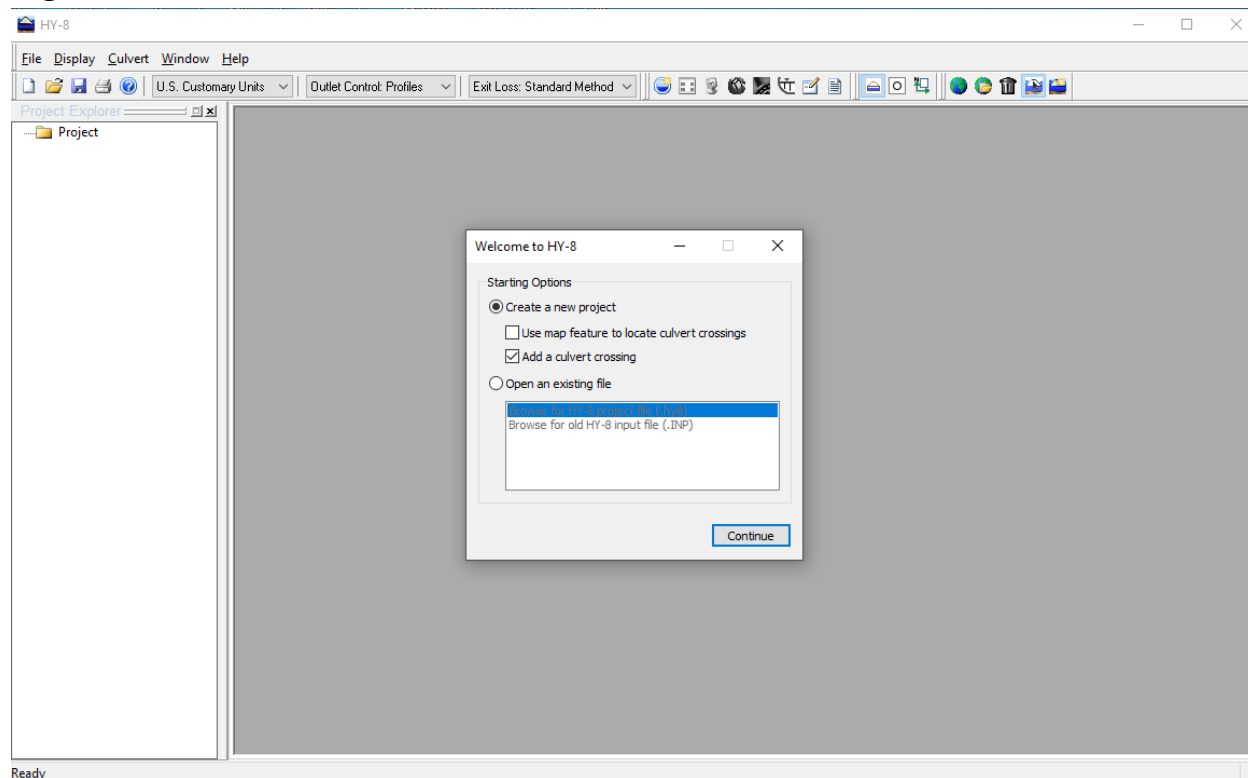
Culvert hydraulic analysis can be completed with the aid of computer software. The following example uses the FHWA HY-8 Culvert Analysis Program and is the computer solution for the same data provided in **Section 5.4.8**.

5.4.8.2 Data Input

Follow **Section 5.4.7** Culvert Design Procedures, Steps 1-3, to obtain input data necessary for the HY-8 program.

Launch HY-8 and create a new project (**Figure 5-32**). After creating a file, the user will be prompted for the discharge range, site data, and culvert shape, size, material, and inlet type.

Figure 5-32. HY-8 Welcome Screen



Change the name to “Existing” and adjust the discharge method to “Recurrence” (**Figure 5-33**).

5.4.8.2.1 Discharge Data

Click “Define...” for the Discharge List. Enter 40 cfs in the row for the 2% AEP (50-year) event and 50 cfs for the row in the 1% AEP (100-year) event (**Figure 5-34**). Press OK.

Figure 5-33. HY-8 Culvert Data Input Screen

The screenshot displays the 'Crossing Data - Crossing 1' window, which is divided into two main sections: 'Crossing Properties' and 'Culvert Properties'.

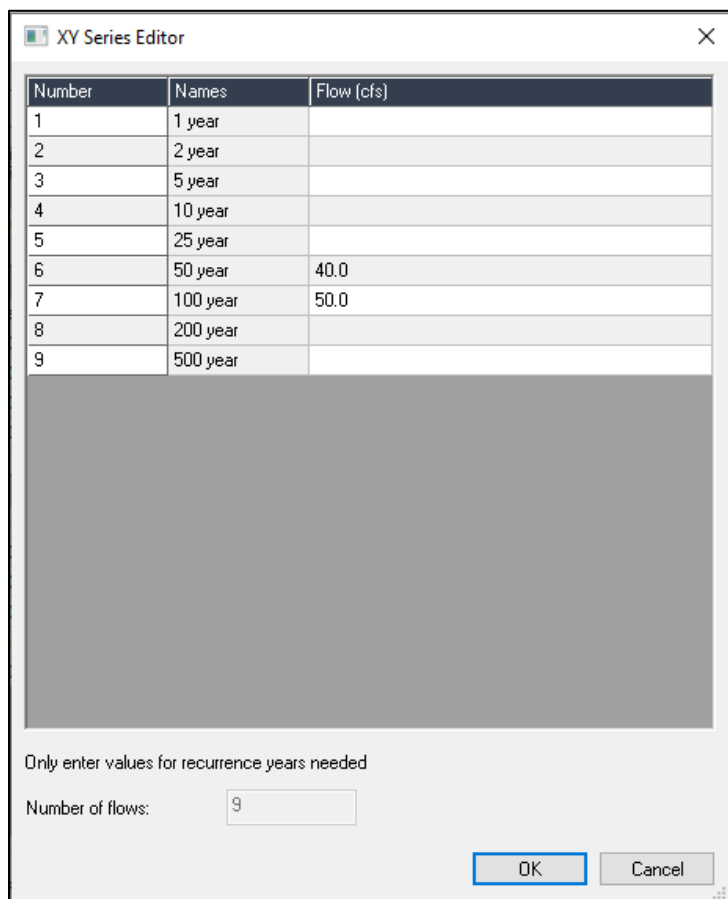
Crossing Properties:

- Name:** Existing
- DISCHARGE DATA:**
 - Discharge Method: Minimum, Design, and Maximum (dropdown)
 - Minimum Flow: Minimum, Design, and Maximum (dropdown)
 - Design Flow: User-Defined (dropdown)
 - Maximum Flow: 0.000 (text input)
- TAILWATER DATA:**
 - Channel Type: Rectangular Channel (dropdown)
 - Bottom Width: 0.000 (text input)
 - Channel Slope: 0.0000 (text input)
 - Manning's n (channel): 0.000 (text input)
 - Channel Invert Elevation: 0.000 (text input)
 - Rating Curve: View... (button)
- ROADWAY DATA:**
 - Roadway Profile Shape: Constant Roadway Elevation (dropdown)
 - First Roadway Station: 0.000 (text input)
 - Crest Length: 0.000 (text input)
 - Crest Elevation: 0.000 (text input)
 - Roadway Surface: Paved (dropdown)
 - Top Width: 0.000 (text input)

Culvert Properties:

- Culvert 1:** (selected in list)
- Buttons:** Add Culvert, Duplicate Culvert, Delete Culvert
- CULVERT DATA:**
 - Name: Culvert 1 (text input)
 - Shape: Circular (dropdown)
 - Material: Concrete (dropdown)
 - Diameter: 0.000 (text input)
 - Embedment Depth: 0.000 (text input)
 - Manning's n: 0.012 (text input)
 - Culvert Type: Straight (dropdown)
 - Inlet Configuration: Square Edge with Headwall (dropdown)
 - Inlet Depression?: No (dropdown)
- SITE DATA:**
 - Site Data Input Option: Culvert Invert Data (dropdown)
 - Inlet Station: 0.000 (text input)
 - Inlet Elevation: 0.000 (text input)
 - Outlet Station: 0.000 (text input)
 - Outlet Elevation: 0.000 (text input)
 - Number of Barrels: 1 (text input)

Bottom Buttons: Help, Click on any icon for help on a specific topic, Low Flow, AOP, Energy Dissipation, Analyze Crossing, OK, Cancel.

Figure 5-34. HY-8 Culvert Flow Rate Data Input Screen

XY Series Editor

Number	Names	Flow (cfs)
1	1 year	
2	2 year	
3	5 year	
4	10 year	
5	25 year	
6	50 year	40.0
7	100 year	50.0
8	200 year	
9	500 year	

Only enter values for recurrence years needed

Number of flows:

OK Cancel

5.4.8.2.2 Tailwater Data

- Change the Channel Type to “Irregular Channel” (**Figure 5-35**)
- Click “Define...” to enter the cross-section data from example in **Section 5.4.8.** (**Figure 5-36**)

Figure 5-2. HY-8 Culvert Data Input Screen

The screenshot displays the 'Crossing Data - Crossing 1' window, which is divided into two main sections: 'Crossing Properties' and 'Culvert Properties'.

Crossing Properties:

- Name:** Existing
- DISCHARGE DATA:**
 - Discharge Method: Recurrence
 - Discharge List: Define...
- TAILWATER DATA:**
 - Channel Type: Rectangular Channel (dropdown menu is open showing options: Rectangular Channel, Trapezoidal Channel, Triangular Channel, Irregular Channel, Enter Rating Curve, Enter Constant Tailwater Elevation)
 - Bottom Width: (blank) ft
 - Channel Slope: (blank) ft/ft
 - Manning's n (channel): (blank)
 - Channel Invert Elevation: (blank) ft
 - Rating Curve: View...
- ROADWAY DATA:**
 - Roadway Profile Shape: Constant Roadway Elevation
 - First Roadway Station: 0.000 ft
 - Crest Length: 0.000 ft
 - Crest Elevation: 0.000 ft
 - Roadway Surface: Paved
 - Top Width: 0.000 ft

Culvert Properties:

- Culvert 1** (selected)
- Buttons: Add Culvert, Duplicate Culvert, Delete Culvert
- CULVERT DATA:**
 - Name: Culvert 1
 - Shape: Circular
 - Material: Concrete
 - Diameter: 0.000 ft
 - Embedment Depth: 0.000 in
 - Manning's n: 0.012
 - Culvert Type: Straight
 - Inlet Configuration: Square Edge with Headwall
 - Inlet Depression?: No
- SITE DATA:**
 - Site Data Input Option: Culvert Invert Data
 - Inlet Station: 0.000 ft
 - Inlet Elevation: 0.000 ft
 - Outlet Station: 0.000 ft
 - Outlet Elevation: 0.000 ft
 - Number of Barrels: 1

Bottom Buttons: Help, Click on any ? icon for help on a specific topic, Low Flow, AOP, Energy Dissipation, Analyze Crossing, OK, Cancel.

Figure 5-336. HY-8 Tailwater Channel Data Input Screen

Irregular Tailwater Channel

Tailwater File

Browse for existing .TW file

Tailwater Channel

Slope of tailwater channel: ft/ft

Number of cross-sec points:

Irregular Channel Cross-Section

No.	Station (ft)	Elevation (ft)	Manning n
1	0.000	855.000	0.0800
2	10.000	854.000	0.0400
3	15.000	851.000	0.0400
4	16.000	850.900	0.0400
5	17.000	850.900	0.0400
6	18.000	851.000	0.0400
7	23.000	854.000	0.0800
8	33.000	855.000	

5.4.8.2.3 Roadway Data

Select “Constant Roadway Elevation.” Enter 100 ft for the Crest Length. Enter 870.0 ft for the Crest Elevation. Enter 36 ft for the Top Width. (Figure 5-37)

Figure 5-37. HY-8 Roadway Data Input Screen

The screenshot displays the 'Crossing Data - Crossing 1' window, which is divided into two main sections: 'Crossing Properties' and 'Culvert Properties'.

Crossing Properties:

- Name: Existing
- DISCHARGE DATA**
 - Discharge Method: Recurrence
 - Discharge List: Define...
- TAILWATER DATA**
 - Channel Type: Irregular Channel
 - Irregular Channel: Define...
 - Rating Curve: View...
- ROADWAY DATA**
 - Roadway Profile Shape: Constant Roadway Elevation
 - First Roadway Station: 0.000 ft
 - Crest Length: 100.000 ft
 - Crest Elevation: 870.000 ft
 - Roadway Surface: Paved
 - Top Width: 36.000 ft

Culvert Properties:

- Culvert 1 (selected)
- Buttons: Add Culvert, Duplicate Culvert, Delete Culvert
- CULVERT DATA**
 - Name: Culvert 1
 - Shape: Circular
 - Material: Concrete
 - Diameter: 0.000 ft
 - Embedment Depth: 0.000 in
 - Manning's n: 0.012
 - Culvert Type: Straight
 - Inlet Configuration: Square Edge with Headwall
 - Inlet Depression?: No
- SITE DATA**
 - Site Data Input Option: Culvert Invert Data
 - Inlet Station: 0.000 ft
 - Inlet Elevation: 0.000 ft
 - Outlet Station: 0.000 ft
 - Outlet Elevation: 0.000 ft
 - Number of Barrels: 1

At the bottom of the window, there are several buttons: Help, Click on any ? icon for help on a specific topic, Low Flow, AOP, Energy Dissipation, Analyze Crossing, OK, and Cancel.

5.4.8.2.4 Culvert Data

Enter 2 ft for the culvert diameter from the example from **Section 5.4.8.** (Figure 5-38)

Figure 5-38. HY-8 Culvert Size Data Input Screen

Crossing Properties

Name: Existing

Parameter	Value	Units
DISCHARGE DATA		
Discharge Method	Recurrence	
Discharge List	Define...	
TAILWATER DATA		
Channel Type	Irregular Channel	
Irregular Channel	Define...	
Rating Curve	View...	
ROADWAY DATA		
Roadway Profile Shape	Constant Roadway Elevation	
First Roadway Station	0.000	ft
Crest Length	100.000	ft
Crest Elevation	870.000	ft
Roadway Surface	Paved	
Top Width	36.000	ft

Culvert Properties

Culvert 1

Add Culvert
Duplicate Culvert
Delete Culvert

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Concrete	
Diameter	2.000	ft
Embedment Depth	0.000	in
Manning's n	0.012	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	0.000	ft
Outlet Station	0.000	ft
Outlet Elevation	0.000	ft
Number of Barrels	1	

Help Click on any icon for help on a specific topic Low Flow AOP Energy Dissipation Analyze Crossing OK Cancel

5.4.8.2.4 Site Data

Enter 850.95 ft for the Inlet Elevation, 48 for the Outlet Station (culvert length), and 850.90 ft for the Outlet Elevation. (**Figure 5-39**)

Figure 5-39. HY-8 Culvert Elevation Data Input Screen

Crossing Properties

Name: Existing

Parameter	Value	Units
DISCHARGE DATA		
Discharge Method	Recurrence	
Discharge List	Define...	
TAILWATER DATA		
Channel Type	Irregular Channel	
Irregular Channel	Define...	
Rating Curve	View...	
ROADWAY DATA		
Roadway Profile Shape	Constant Roadway Elevation	
First Roadway Station	0.000	ft
Crest Length	100.000	ft
Crest Elevation	870.000	ft
Roadway Surface	Paved	
Top Width	36.000	ft

Culvert Properties

Culvert 1

Add Culvert

Duplicate Culvert

Delete Culvert

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Concrete	
Diameter	2.000	ft
Embedment Depth	0.000	in
Manning's n	0.012	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	850.950	ft
Outlet Station	48.000	ft
Outlet Elevation	850.900	ft
Number of Barrels	1	

Help Click on any icon for help on a specific topic Low Flow AOP Energy Dissipation Analyze Crossing OK Cancel

Click “Analyze Crossing” to analyze the existing culvert and interpret the results. Change the Display to “Culvert Summary Table” to interpret the results. (Figure 5-40)

Figure 5-40. HY-8 Culvert Summary Table Screen

Discharge Names	Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth(ft)	Outlet Control Depth(ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
50 year	40.00	40.00	858.86	7.91**	7.66	4-FFf	2.00	2.00	2.00	2.66	12.73	2.13
100 year	50.00	50.00	862.74	11.79**	10.78	4-FFf	2.00	2.00	2.00	2.94	15.92	2.25

Display

☐ Crossing Summary Table
☒ Culvert Summary Table Culvert 1
☐ Water Surface Profiles
☐ Tapered Inlet Table
☐ Customized Table Options...

Geometry

Inlet Elevation: 850.95 ft
 Outlet Elevation: 850.90 ft
 Culvert Length: 48.00 ft
 Culvert Slope: 0.0010
 Inlet Crest: 0.00 ft
 Inlet Throat: 0.00 ft

Plot

Outlet Control: Profiles

** An unsteady, oscillatory hydraulic jump is possible, but full flow is likely.

5.4.8.3 Find Proposed Alternatives

From the main menu, copy the “Existing” culvert and rename to “Proposed 42 inch Dia.” (Figure 5-41 and Figure 5-42)

Figure 5-41. HY-8 Duplicate Culvert Screen

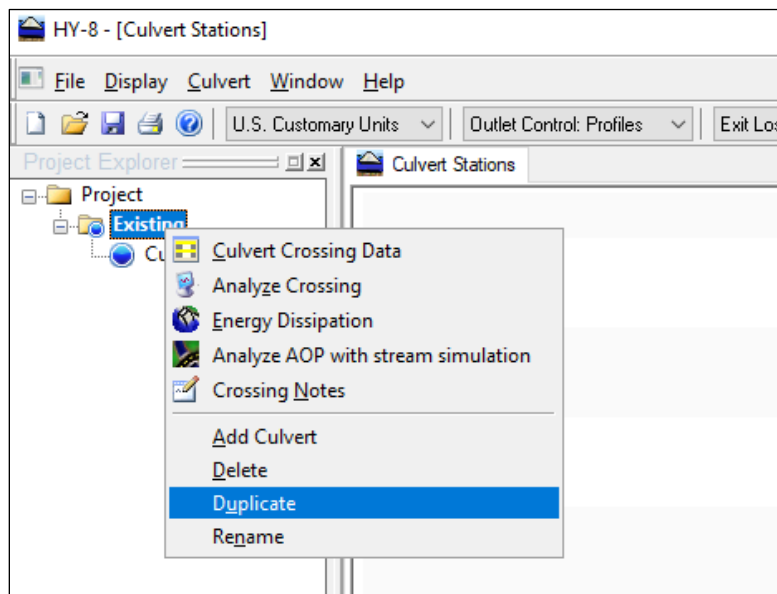
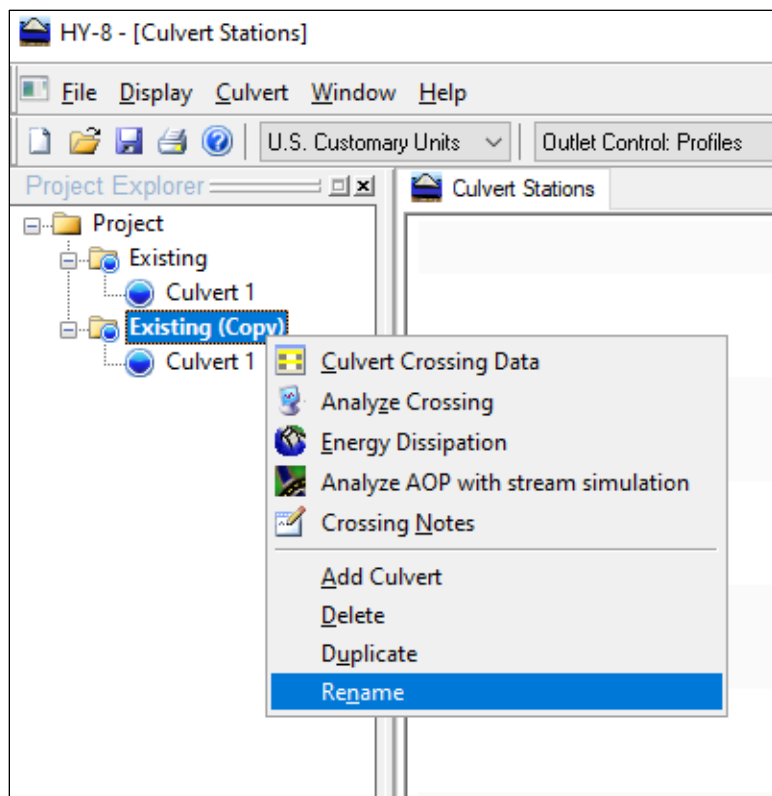


Figure 5-42. HY-8 Rename Culvert Screen



5.4.8.3.1 Culvert Data

Change the culvert material to “Corrugated Steel”, the culvert diameter to 3.5 ft, and the inlet configuration to “Square Edge with Headwall.” (Figure 5-43)

Figure 5-43. HY-8 Update Culvert Material Screen

Crossing Properties

Name:

Parameter	Value	Units
DISCHARGE DATA		
Discharge Method	Recurrence	
Discharge List	Define...	
TAILWATER DATA		
Channel Type	Irregular Channel	
Irregular Channel	Define...	
Rating Curve	View...	
ROADWAY DATA		
Roadway Profile Shape	Constant Roadway Elevation	
First Roadway Station	0.000	ft
Crest Length	100.000	ft
Crest Elevation	870.000	ft
Roadway Surface	Paved	
Top Width	36.000	ft

Culvert Properties

Culvert 1

Add Culvert
Duplicate Culvert
Delete Culvert

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Corrugated Steel	
Diameter	3.500	ft
Embedment Depth	0.000	in
Manning's n	0.024	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	850.950	ft
Outlet Station	48.000	ft
Outlet Elevation	850.900	ft
Number of Barrels	1	

Help Click on any ? icon for help on a specific topic Low Flow AOP Energy Dissipation Analyze Crossing OK Cancel

5.4.8.3.2 Site Data

- Lower the upstream invert to 850.45 ft and the downstream invert to 850.40 ft to recess the culvert 6 inches. (**Figure 5-44**)
- Note: invert recessed depth exceeds required $0.1 \times \text{rise}$

Figure 5-44. HY-8 Culvert Invert Lowering Screen

Crossing Properties

Name:

Parameter	Value	Units
DISCHARGE DATA		
Discharge Method	Recurrence	
Discharge List	Define...	
TAILWATER DATA		
Channel Type	Irregular Channel	
Irregular Channel	Define...	
Rating Curve	View...	
ROADWAY DATA		
Roadway Profile Shape	Constant Roadway Elevation	
First Roadway Station	0.000	ft
Crest Length	100.000	ft
Crest Elevation	870.000	ft
Roadway Surface	Paved	
Top Width	36.000	ft

Culvert Properties

Culvert 1

Add Culvert
Duplicate Culvert
Delete Culvert

Parameter	Value	Units
CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Corrugated Steel	
Diameter	3.500	ft
Embedment Depth	0.000	in
Manning's n	0.024	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	850.450	ft
Outlet Station	48.000	ft
Outlet Elevation	850.400	ft
Number of Barrels	1	

Help Click on any icon for help on a specific topic Low Flow AOP Energy Dissipation Analyze Crossing OK Cancel

Click “Analyze Crossing” to analyze the existing culvert and interpret the results. Change the Display to “Culvert Summary Table” to interpret the results. (**Figure 5-45**)

Figure 5-45. HY-8 Culvert Summary Table Screen

The screenshot shows the 'Culvert Summary Table - Culvert 1' window. It features a table with 13 columns: Discharge Names, Total Discharge (cfs), Culvert Discharge (cfs), Headwater Elevation (ft), Inlet Control Depth(ft), Outlet Control Depth(ft), Flow Type, Normal Depth (ft), Critical Depth (ft), Outlet Depth (ft), Tailwater Depth (ft), Outlet Velocity (ft/s), and Tailwater Velocity (ft/s). The table contains three rows of data for Base, Q50, and Q100 discharges. Below the table is a large gray area for plots. At the bottom, there are several configuration panels: 'Display' with radio buttons for 'Crossing Summary Table', 'Culvert Summary Table' (selected), 'Water Surface Profiles', 'Tapered Inlet Table', and 'Customized Table'; 'Geometry' with fields for Inlet Elevation, Outlet Elevation, Culvert Length, Culvert Slope, Inlet Crest, and Inlet Throat; 'Plot' with buttons for 'Crossing Rating Curve', 'Culvert Performance Curve', 'Selected Water Profile', and 'Water Surface Profile Data'; and 'Outlet Control' set to 'Profiles'. A row of buttons at the very bottom includes Help, Flow Types..., Edit Input Data..., Energy Dissipation..., AOP..., Low Flow..., Export Report, Adobe PDF (*.pdf), and Close.

Discharge Names	Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth(ft)	Outlet Control Depth(ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
Base	0.00	0.00	850.90	0.00	0.45	0-NF	0.00	0.00	0.50	0.00	0.00	0.00
Q50	40.00	40.00	854.22	2.96	3.77	3-M2t	3.50	1.97	3.16	2.66	4.38	2.13
Q100	50.00	50.00	854.87	3.42	4.42	7-M2t	3.50	2.21	3.44	2.94	5.22	2.25

5.4.8.4 Rating Curve

Use a rating curve for $(d_c + D) / 2$ if values are greater than the calculated tailwater. Contact the Hydraulic Unit Supervisor for rating curve spreadsheets that can be used to develop the rating curve.

5.5 Temporary Culverts

5.5.1 Temporary Culverts

When replacing culverts conveying inland streams (Part 301), it is necessary to provide temporary flow diversion through the project area. Temporary flow diversion includes pumps, culverts, diversion channels, etc. At a minimum, the discharge through the temporary flow diversion is required to pass the 10% probability of exceedance and provide a dry construction site at the corresponding return interval (refer to **Table 5-5**). In addition, flow through the temporary and construction site flow path is required to pass a range of flows up to and including the 1% AEP (100-year) storm without harmful interference. This is typically done by limiting the top height of a cofferdam or providing a water surface elevation that triggers removal. Smaller discharges may be used to match the capacity of an existing undersized system upon approval of the Hydraulic Unit Supervisor for trunkline projects.

Temporary crossings on inland streams (Part 301) or those with a contributing drainage area equal or greater than 2 square miles (Part 31) require a permit from EGLE (refer to EGLE's Hydraulic Report Guidelines). Analyze the temporary drainage for a range of flows up to and including the 1% AEP (100-year) discharge.

If the water diversion causes backwater over the existing conditions, provide a maximum water surface elevation on the plans that requires immediate removal of the diversion or provide maximum cofferdam height elevation to allow for overtopping to prevent harmful interference. Develop the water surface elevation for diversion removal or maximum cofferdam height elevation based on the duration of the temporary condition, the temporary design recurrence interval (refer to **Table 5-5** and the elevation at which a potential harmful interference would occur. Identify expected overtopping point(s) along the temporary structure.

Consider using a larger discharge for temporary design if the impacts of removing the water diversion or overtopping the cofferdam and flooding the work site during larger events are problematic (overtopping, road closures, site damage, etc.), particularly on higher road classifications, such as interstates, divided highways, and principal arterials. Provide staging for drawdown of impounded water to avoid harmful interference.

$$P = \left(1 - \left(1 - \frac{1}{T}\right)^n\right) \times 100 \quad (5.14)$$

Where: P = Probability of Exceedance (%)
 T = Recurrence Interval, years
 n = number of years

Table 5-5. Corresponding AEP/ARI for 10% Probability of Exceedance

Temporary Duration (n)	Corresponding AEP/ARI for 10% Probability of Exceedance (T)
2 months or less	50% (2-year)
2 months to 6 months	20% (5-year)
6 months to 1 year	10% (10-year)
1 year to 2 years	*4% (25-year)

For diversions in place over the winter, assume a temporary duration of at least 2 years (n = 2 years).

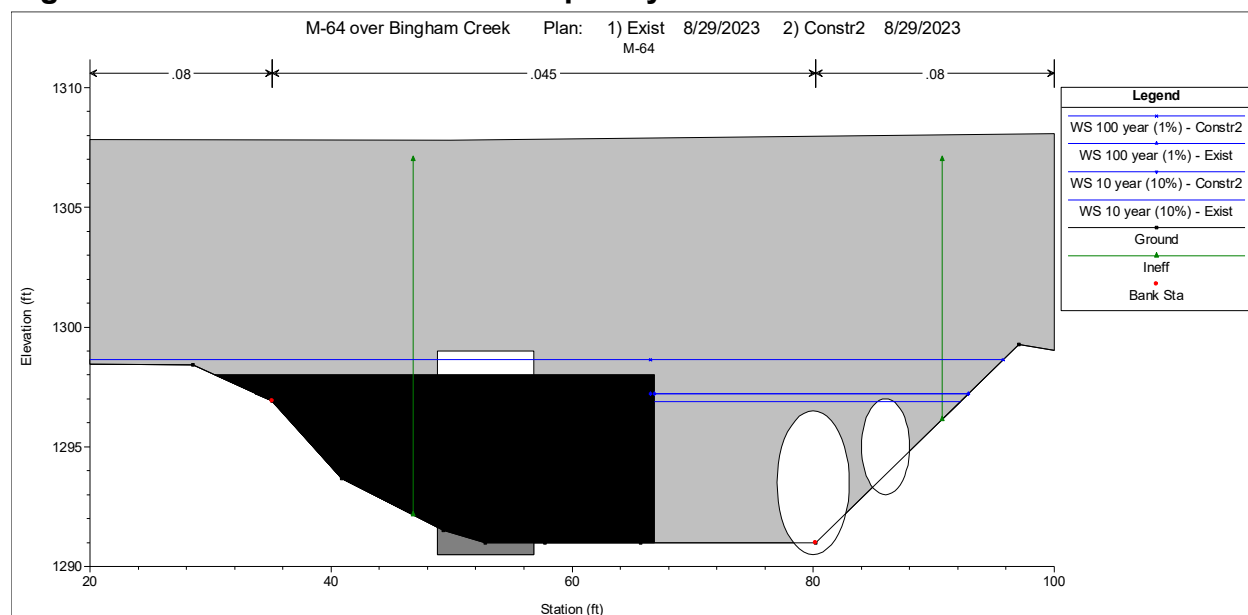
Use a maximum of 10% AEP (10-year) for local roads and collector systems with ADT<3000 VPD.

Provide temporary flow management information in the plans that are necessary to obtain an EGLE permit and to provide a biddable solution for handling temporary flows during construction (bypass pumping, diversion channel, temporary culvert, etc.). The contractor has the ultimate responsibility to choose specific temporary flow management methods.

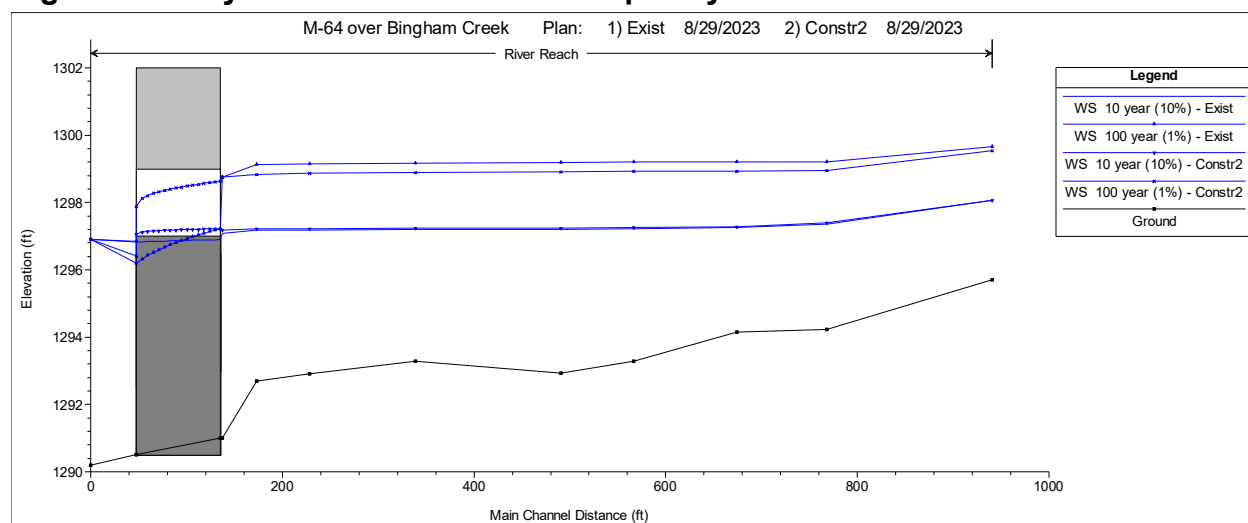
5.5.2 Example Problem

Replace an existing 8 ft x 8 ft box culvert conveying an inland stream (Part 301) with a 20 ft x 12 ft box culvert under a two-lane M-Route. Assume construction will be less than 1 year. Sheet pile cofferdams will be used for the culvert construction work zone. Determine the required AEP for temporary design and identify sheet pile cofferdam overtopping height and required culvert sizes for bypass flow during construction. This site has a 1% AEP flow of 420 cfs and a 10% AEP flow of 150 cfs.

- Step 1** From **Table 5-5**, based on a 1 year or less construction period, use a 10% AEP (10-year) storm for design of the overtopping elevations and temporary structures. The temporary bypass is required to pass 150 cfs at a minimum. Ensure outlet velocity and erosion protection requirements from **Section 5.3.4.6** are met for the temporary condition.
- Step 2** Prepare HEC-RAS models for existing and proposed conditions following guidance in Chapter 6, Bridge Hydraulic Design. This step establishes the size of the temporary culverts to pass the 10% AEP without overtopping the cofferdam. This is an iterative process to balance bypass flows, culvert sizes, and cofferdam height. The initial sizes may be revisited in Step 3. The cross-section showing the 10% AEP (10-year) storm bypassing the existing culvert is shown in **Figure 5-46**.

Figure 5-46. Cross-Section with Temporary Culverts and Cofferdam

Step 3 This step verifies that the combined flow through the temporary culverts and the cofferdam can pass the 1% AEP (100-year) storm without causing harmful interference. Refer to the HEC-RAS profile in **Figure 5-47** showing the cofferdam is overtopped for larger storms and meets harmful interference requirements.

Figure 5-47. Hydraulic Profile of the Temporary Culverts and Cofferdam

Step 4 Document hydraulic analysis and results in the Drainage Study. Incorporate bypass culvert sizes, invert elevations and cofferdam height elevations in the culvert staging plans.

5.6 Maintenance

5.6.1 Culvert Maintenance and Inspection

Culvert maintenance is required to follow the work methods described in the MDOT Maintenance Activity Guides 1280-Culvert Underdrain & Edge Drain Cleaning and 1281-Culvert Drainage Structure Underdrain & Edge Drain Maintenance.

Evaluate culvert designs to minimize future maintenance needs. Key maintenance items for culverts include sedimentation, debris passage, and erosion protection.

The Ancillary Structures Program is responsible for culvert inspection within MDOT. For more details refer to [Michigan Ancillary Structures Inspection Manual](#) (MiASIM).

5.6.2 Lining Culverts

When a culvert has structural deterioration, it may be possible to line the culvert instead of replacing it. A hydraulic analysis is required to determine the potential impacts of inserting a liner. Analyze a range of flows passed by the culvert.

Examples of culvert lining include, but not limited to, inserting a plastic pipe in the existing culvert and grouting the annulus or inserting a resin-impregnated flexible liner. Installation is covered by the appropriate Special Provision, e.g., “Cured-In-Place Pipe Liner for Culverts and Storm Sewer.” Installation of a liner is allowed for the following conditions:

- The culvert is a cross-culvert that acts as an equalizer between two bodies of water (e.g., between two wetlands, these culverts are extremely rare in Michigan).
- A driveway culvert that is only carrying ditch flow generated from MDOT ROW. For the range of design flows, the water surface elevation upstream of the culvert is contained within the ROW.
- The culvert is a CMP that does not experience inlet control over the range of design flows.

Direct any questions regarding the hydraulic analysis or potential impacts to the Hydraulic Unit Supervisor for trunkline projects.

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